Electromechanical Coupled Vibration between Traction Motor and Bogie of High-Speed Train

Zhiqiang Zhang¹, a, Xinying Zhao*², b, Xiangfei Li¹, Fei Lin², Zhongping Yang²

¹ CRRC Qingdao Sifang Co., Ltd., Qingdao, 266000, China
² School of Electrical Engineering, Beijing Jiaotong University, Beijing, 100044, China

a email: zzqiang@cqsf.com, b email: 14121518@bjtu.edu.cn

Keywords: Harmonic Torque; Electromechanical Coupled Vibration; Resonance Frequency

Abstract. In high-speed train, the harmonics generated in inverter due to control and nonlinear of switch may lead to the torque ripple in different frequency and amplitude. The driving device which consists of rotor, coupling, gear, shift and wheels of bogie has some resonance frequencies. When there are frequencies which are same or close to the resonance frequency of shifts in the torque pulsation, the shifts would be vibrated. First the paper analyzes the cause and influence of the torque pulsation. Then the author calculates the vibration frequencies of drive devices. Finally the author simulates the coupling system of driving motor and bogie driving device.

Introduction

High-speed train’s traction drive system is an electromechanical coupling system, In the process of traction operation, traction motor produces torque to the wheels through driving devices, ultimately driving train moving at high speed. To ensure the reliability and absolute security of high-speed train, the traction force and torque should be output stably, otherwise the shaft vibration caused by motor torque ripple will affect the life of device and operation security of train.

Currently, there are many international reports about this, mainly about driving device especially for locomotive. References [1-3] studied on failure of mechanical part when electrical part is failure. References [4] analyzed vibration state in bogie-mounted traction system of locomotive. These papers all focus on torsional vibration just from the view of machinery. This paper mainly analyzes the forced vibration of the mechanical structure when excited by motor torque ripple.

The Low-Frequency Harmonic Torque of Traction Motor

Ultraharmonics in inverter usually caused by switching action, but switching devices are not ideal in reality, so there are severe distortions of current and low-frequency torque ripple which mainly caused by dead-time of switches[5].

![Waveform of output voltage affected by dead-time.](image)

Fig.1. Waveform of output voltage affected by dead-time. The error voltage pulse in Fig. 1(d) can be equivalent to a square-wave voltage $u_{eq}$ and its...
amplitude $U_{eq}$ is:

$$U_{eq} = f_c U_c T_d$$  \hspace{1cm} (1)

In the type: $f_c$ is carrier frequency, $T_d$ is dead-time.

$u_{ef}$ can be expressed by FFT:

$$u_{ef} = \frac{4U_{eq}}{\pi}(\sin \omega t + \frac{1}{5}\sin 5\omega t + \frac{1}{7}\sin 7\omega t + \cdots - \sin n\omega t)$$  \hspace{1cm} (2)

In the type (2): $\omega$ is stator frequency, $n$ is odd number and not the multiple of 3.

The simulation is based on the motor control model in CRH2A EMUs, the 5th current harmonic of different dead-time are shown in Fig.2.

![Fig.2. Percentage of 5th harmonic on fundamental current](image1)

The 5th and 7th current harmonics will result low-frequency harmonic torque and the pulsation frequency is six times the stator fundamental frequency [6].

![Fig.3. Torque pulsation waveforms](image2)

5th harmonic results in low frequency torque ripple and the pulsation frequency (397.2Hz) is six times the stator fundamental frequency (66.2Hz), and the peak-to-peak values of the torque pulsation increases from 280N.m to 420N.m.

**Mechanical Vibration of driving device**

To have a comprehensive consider about shaft vibration frequency, drive system is divided to 5 parts based on following assumptions [7]:

1. Without regard to efficiency of powerdriven transmission and gap of drive system;
2. Without regard to the elasticity of train axle, gear, gear shaft and so on;
3. Drive, driving elements are seen as lumped mass.
Lumped mass analysis model of driving system as shown in Fig. 5, drive devices are equivalent to disks that have inertia connected by 4 axles.

\[ J_1 J_2 J_3 J_4 J_5 \]
\[ K_1 K_2 K_3 K_4 \]

Fig.5. Lumped mass analysis model of drive system

In the type: \( J_i \) is equivalent rotational inertia and \( K_i \) is equivalent torsional rigidity.

The basis mechanics equation can be established according to the lumped mass model [8]:

\[ J \ddot{\theta} + K \theta = 0 \]  \hspace{1cm} (3)

The characteristic root of equation (3) is:

\[ \theta_i = A_i \sin(\omega t + \phi) \]  \hspace{1cm} (4)

Substitute into (3):

\[ (K - \omega^2 J) A = 0 \]  \hspace{1cm} (5)

In the type: \( A \) is column vector of amplitude, \( \omega \) is shaft free vibration frequency.

\( A \) must be satisfied to have non-zero solutions:

\[ |K - \omega^2 J| = 0 \]  \hspace{1cm} (6)

So we can get free vibration frequency according to parameters:

\( \omega_1 = 51.13 \) rad/s
\( \omega_2 = 113.82 \) rad/s
\( \omega_3 = 173.35 \) rad/s
\( \omega_4 = 1322.70 \) rad/s

The mechanical structure model of drive system is established by SimMechanics in Matlab, and then analyses the vibration frequency by simulation.

Fig.6. Simulation model in SimMechanics

Linearize the system and then draw bode plots of motor torque to rotation angle, angular velocity and angular acceleration of wheel considering damping factor, as shown in Fig.7 in turn.
As it is clear from Fig.7 that there are 3 resonance point considering system damping shown as Table.1:

<table>
<thead>
<tr>
<th>Number</th>
<th>Resonant frequencies/rad/s</th>
<th>peak gains /dB</th>
<th>Resonant frequencies /Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_1$</td>
<td>72.5</td>
<td>8.65</td>
<td>11.54</td>
</tr>
<tr>
<td>$\omega_2$</td>
<td>151</td>
<td>18.86</td>
<td>24.04</td>
</tr>
<tr>
<td>$\omega_3$</td>
<td>233</td>
<td>15.87</td>
<td>37.10</td>
</tr>
</tbody>
</table>

Damped vibration frequencies of drive system are increased compared with free vibration, and a free vibration frequency disappears when considering damping factor. Resonant frequencies of rotation angle, angular velocity and angular acceleration of wheel are consistent, and the peak gains of angular acceleration exceed 0dB, so the driving system will vibrate persistently if the system input contains the same frequency components like resonant frequencies.

**Shaft Torsional Vibration Considering Electromechanical Coupling**

The torque pulsation frequency of traction motor is six times the stator fundamental frequency and the resonance frequency of drive system are nearly 30Hz according to the analysis and results above, the train runs at low speed this moment. In this chapter, take $\omega_3$ (37.1Hz) as an example to show shaft torsional vibration.

Resonant frequency $\omega_3$=37.1Hz, frequency of motor torque pulsation is the same with $\omega_3$ when the frequency of motor stator is 6.183Hz, It can be calculated that corresponding running speed of train is about 7km/h. So we can get the FFT of motor current when train runs at 7km/h by simulation as shown in Fig.8.

As it is clear from the simulation result in Fig.8, there are mainly 5th, 7th, 11th and 13th current
harmonics.

The models of motor control and torsional vibration are connected, the joint simulation is realized, and then the vibration performance can be observed by angular acceleration of pinion. The simulation condition is: train accelerates from 0km/h to 7km/h in 2.5 seconds, and then runs at a constant speed of 7km/h after 2.5 seconds.

![Fig.9. Comparison of torque pulsation and shaft torsional vibration](image)

As it is shown in Fig. 9 that there are obvious low-frequency torque pulsations after 2.5 seconds, and the ripple frequency is 37Hz, which is six times the stator frequency (6.183Hz).

![Fig.10. Partial enlarged views of torque pulsation and shaft torsional vibration](image)

In the Fig.9 and Fig.10, the torsional vibration is weak during the accelerative state in 2.5 seconds, but the vibration amplitudes after 2.5 seconds increased by 4 times compared with the previous 2.5 seconds, and the vibration frequency is completely consistent with torque ripple frequency. So if train runs at the resonant speed, the shaft torsional vibration will be serious.

Observe torque pulsation and shaft torsional vibration between 1.7-2.2s as shown in Fig.11, the torque pulsation and shaft vibration aggravated between 1.85-2.05 seconds and then slowed down.

![Fig.11. Partial enlarged views of torque pulsation and shaft torsional vibration](image)
From the above figure, it can be calculated that the torque ripple frequency in the 2 seconds is 151rad/s, which is the same with resonant frequency \( \omega_3 \) (24.04Hz) of drive system in Tab1.

So shaft torsional vibration between traction motor and bogie is serious when the torque ripple frequency is close to natural vibration frequency of drive devices, which will affect the life of device and operation security of train.

**Conclusion**

In high-speed train, the low frequency harmonic torque and electromechanical coupled vibration in traction drive system have been studied theoretically as well as simulation, and we can get the following conclusions:

(1) Nonlinear factors of inverter could result in obvious low frequency components in traction motor torque, especially for dead-time effect, which produces 5th, 7th current harmonics and 6th pulse harmonic torque.

(2) The natural vibration state has been researched by the model of drive system, and there are three lower natural vibration frequencies when considering system damping: 11.54Hz, 24.04Hz and 37.10Hz.

(3) The drive system can be coupling vibrated obviously when output torque contains natural frequencies above at certain speeds, and there are two resonance speeds of train.

**References**


