Analysis of Wheel-rail Force Characteristics of Type A Metro Bogie with a Speed of 80 km/h

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Abstract. In this paper, the wheel-rail force analysis test is carried out on the type A metro vehicle equipped with a certain type bogie and the maximum operating speed is 80km/h. The purpose is to explore the characteristics of derailment coefficient, wheel unloading ratio and wheelset lateral force under different conditions. According to UIC518, the safety, ride index and stability of subway vehicles under AW0(AW0 means “no load”) and AW3(AW3 means “overload”) are evaluated. Through the analysis of this paper, it is found that when the train runs on the R300-meter curve, the various indicators are the largest, followed by the R500-meter curve, and the smallest on the straight line. The derailment coefficient and the wheelset lateral force of the motor car are greater than those of the trailer. The various wheel-rail force indicators of this type of subway bogie all meet the requirements.

1. Introduction
Wheel-rail force is an important indicator of train running status, which can realize derailment prediction, determine wheelset wear and fatigue, calibrate track force, and even limit train running speed. Many scholars have conducted detailed studies on the characteristics of wheel-rail force. Yang Z.[¹] introduced several test methods of wheel-rail force, analyzed their advantages and disadvantages, and put forward suggestions on the optimization of test methods. Caiying H.[²] used multi-rigid body dynamics software to establish a train dynamics model, and studied the influence of various wheel diameter differences on wheel-rail lateral forces through dynamic simulation. Jiyi T.[³] evaluated the derailment safety of a test line and used the force-measuring rail method to test the wheel-rail force of the test line, including the wheel-rail vertical and lateral force. The derailment coefficient and the wheel unloading ratio was calculated from the wheel-rail force. Test results show that the derailment coefficient and the wheel unloading ratio are far less than the limit value, both have a large safety margin.

In order to study the wheel-rail force characteristics of a certain type of subway bogie, the dynamic test of this type of subway vehicle was carried out. The lateral and vertical forces between the wheel and rail are obtained by force measuring wheelset, and the derailment safety is evaluated by calculating the derailment coefficient, the rate of wheel unloading ratio and so on. The force measuring wheel set is a special sensor that measures the force of the wheel and rail. Usually, strain gauges are arranged on the wheel web of the force measuring wheel to form a measuring bridge[⁴] (see Figure 1). The train is composed of four motor cars and two trailers (+Tc-Mp-M+M-Mp-Tc+), and the test objects include TC01 and MP02 vehicle bodies and their first bogie. There are a total of two force measuring wheelsets, which are respectively installed on the first axle of the vehicle. The...
test load conditions include empty (AW0) and overload (AW3) conditions.

Fig.1. Vertical force measurement bridge by discontinuous measurement method

Fig.2. The lateral force measurement bridge of the discontinuous measurement method

The test data collector uses the German HBM Somat eDaq data acquisition system, the number of effective data channels for a single data acquisition terminal is 128, the sampling between channels is strictly synchronized, and the vibration acceleration sampling frequency is 2kHz. The data acquisition terminal has an independent embedded controller to run the data acquisition program and is equipped with independent data storage. The memory uses solid-state hard drives to meet data security requirements under harsh conditions.

2. Characteristics of Derailment Coefficient

The derailment coefficient is used to assess whether the wheel rim of the vehicle will climb onto the rail head and derail under the action of lateral force. The derailment coefficient is the ratio of the lateral force $Q$ of the wheel acting on the rail and the vertical force $P$ acting on the rail, namely: $Q/P$. The derailment coefficient is formulated according to the derailment conditions of wheel climbing. Considering the critical conditions of the derailment between wheel and considering a certain safety margin, the evaluation limit is made. The critical value of the derailment coefficient is calculated as follows:

$$
\frac{Q}{P} = \frac{\tan \alpha - \mu}{1 + \mu \tan \alpha}
$$

Where $\alpha$ is the wheel flange angle, and $\mu$ is the wheel-rail friction coefficient. The UIC518 standard stipulates that the limit of the derailment coefficient is 0.8.

In order to compare the difference of the derailment coefficients of the vehicle on the straight line, the R500-meter curve, and the R300-meter curve, the average value of the derailment coefficient of
the motor car and the trailer under the AW3 condition is selected for analysis, and the result is shown in Fig.3. It can be seen from the figure that the derailment coefficient of the R300-meter curve is the largest, followed by the R500-meter curve, and the derailment coefficient of the straight line is the smallest. The derailment coefficients of the R300-meter curve and R500-meter curve gradually decrease with the increase of speed, and the derailment coefficient hardly changes with speed when the vehicle runs on the straight line.

Fig.4. Derailment coefficient at R300-meter curve

In order to analyze the derailment coefficient at the R300-meter curve, the derailment coefficients under the AW0 and AW3 working conditions are analyzed, as shown in Fig.4. It can be seen that the derailment coefficient of the motor car is greater than that of the trailer. The derailment coefficient of the motor car under the AW0 working condition increases with speed, which is different from other working conditions.

The scatter plot of the maximum value of the derailment coefficient data of the motor car at the R300-meter curve under the AW0 working condition is shown in Fig.5. This figure also reveals the trend that the maximum derailment coefficient at each speed level increases with the increase in speed.

Fig.5. Scatter plot of derailment coefficient(R300-meter_MP_AW0)

3. The law of wheel unloading ratio

The wheel unloading ratio is another derailment safety index for evaluating derailment caused by excessive wheel load shedding. The rate of the wheel load reduction is the ratio of the wheel load reduction $\Delta P$ to the average static wheel weight $\bar{P}$ of the axle, namely: $\frac{\Delta P}{\bar{P}}$. The vertical static load of the wheel and rail is represented by $P_{st}$, then the formula for calculating the wheel unloading ratio is as follows:
\[ \frac{\Delta P}{P} = \frac{|P_R - P_L|}{P_{st}} \]

Where \( P_L \) and \( P_R \) are the static axle loads of the left and right wheels respectively. UIC518 stipulates that when the air spring is normal, the limit of \( \Delta P/P \) is 0.6.

![Fig. 6. Wheel unloading ratio under AW0 load](image)

The average values of the wheel unloading ratio at the straight line, the R500-meter curve and the R300-meter curve under the load conditions of AW0 and AW3 are selected for analysis. The results are shown in Fig.6. It can be seen from the figure that under AW0 working condition, the larger the curve radius is, the smaller the wheel load reduction rate is. The wheel unloading ratio of the trailer at R300-meter curve is greater than that of the motor car, and the wheel unloading ratio of the motor car at R500-meter curve is greater than that of the trailer. The wheel unloading ratios of the motor car and the trailer at the straight line are relatively close.

![Fig. 7. Wheel unloading ratio at R500-meter curve](image)
In order to analyze the wheel unloading ratio at the R500-meter curve, the average value of the wheel unloading ratio of the motor car and the trailer under the normal condition of the air spring is analyzed, as shown in Fig.7. It can be seen that the wheel load reduction rate of the motor car under the AW0 condition is greater than that of the trailer, and the opposite is true under the AW3 condition. Under the condition of AW0, the wheel load reduction rate increases with the increase of speed, but it is opposite under the condition of AW3. In order to further analyze the phenomenon that the wheel unloading ratio at R500-meter curve decreases with the increase of speed under AW3 conditions, points are taken every 100 meters to calculate the wheel unloading ratio. The scatter diagram of its distribution with speed is shown in Fig.8.

4. Analysis of wheelset lateral force

The wheelset lateral force \( H \) is the sum of the left and right wheel-rail lateral forces of the same wheelset. It is used to assess whether the excessive lateral force will cause the gauge to widen or the line to be seriously deformed during the operation of the vehicle. Various dynamics standards have different requirements for the evaluation index of the wheelset lateral force. The UIC518 stipulates that the evaluation value of the wheelset lateral force is calculated as follows:

\[
H = 15 + P_0 / 3
\]

Where \( P_0 \) is the static axle load, and the unit of force in the formula is kilonewton (kN). Through this formula, the limit of lateral force of the axle in this paper is calculated as shown in Table 1. The limit of wheelset lateral force under different loads calculated by this formula are shown in Table 1.

| Load | TC1     | MP1     |
|------|---------|---------|
| AW0  | 37.62kN | 36.47kN |
| AW3  | 50.17kN | 53.28kN |

In order to analyze the wheelset lateral force under different working conditions, the average value of the wheelset lateral force of the trailer and the motor car under AW0 and AW3 were analyzed, the results are shown in Fig.9. It can be seen from the figure that the wheelset lateral force of the R300-meter curve is greater than that of the R500-meter curve and the straight line. The wheelset lateral force of the motor car on the R300-meter curve and the R500-meter curve is greater than that of the trailer, and the wheelset lateral force on the straight line of the motor car and the trailer is close.

For the R500-meter curve and R300-meter curve, the wheelset lateral force increases with the increase of speed, which is obviously affected by the speed. The wheelset lateral force on the straight line gradually decreases with the increase of speed, but the influence of speed is not obvious.

In order to compare the wheelset lateral force under different loads, the wheelset lateral force at the R500-meter curve is selected for analysis. The average value of the wheelset lateral force of the motor
car and the trailer is shown in Fig.10. It can be seen that the wheelset lateral force under AW3 is obviously greater than that under AW0. The wheelset lateral force under various working conditions are all below the limit.

![Fig.9. Wheelset lateral force under AW0 load](image1)

![Fig.10. Wheelset lateral force at R500-meter curve](image2)

5. Conclusions

By analyzing the wheel-rail force characteristics of a type A metro vehicle equipped with a certain type of bogie, the following conclusions can be drawn:

The derailment coefficient, wheel unloading ratio and wheelset lateral force when the train is running on the R300-meter radius curve are the largest, followed by the R500-meter curve, and the straight line is the smallest. When the train runs on the straight line, the changes of these indexes with speed are small. When the train runs on the R300-meter curve and the R500-meter curve, these indexes change more with speed.

Comparing the motor car and the trailer, the derailment coefficient and the wheelset lateral force of the motor car are greater than those of the trailer, but the wheel unloading ratio of the motor car is not all greater than the trailer. Analysis shows that the various wheel-rail force indicators of this type of subway bogie all meet the requirements.

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