Influence of wheel-diameter difference of the same locomotive on ride quality of locomotive

Bin Zhao¹, Fei Liu¹, ⁴, Ruiyu Li¹, Jianming Wang², Lin Liang¹, ³ and Ailing Luo¹

¹School of Mechanical Engineering, Xi’an Jiaotong University, Xi’an 710049, China
²Qinghai Huading Heavy Machine Tool Co., Ltd., Xining 810000, China
³Key Laboratory of Education Ministry for Modern Design and Rotor-Bearing System, Xi’an Jiaotong University, Xi’an 710049, China
⁴E-mail: fayelau@xjtu.edu.cn

Abstract. The existence of wheel-diameter difference of track locomotive will directly affect the motion performance of locomotive. In this paper, the creep force of coaxial wheel-diameter difference is analysed, and the dynamic model of 2-axle bogie locomotive is established by SIMPACK software. Based on the study of two typical wheel-diameter difference of the same bogie, 10 special working conditions of wheel-diameter differences of the same locomotive are put forward. The effects of different working conditions and different wheel-diameter differences of the same working condition on the straight line motion performance of locomotive are analysed. The results show that, the lateral displacement and lateral ride quality index of locomotive body increase with the increase of wheel-diameter difference under the same working condition, and they do not exceed the safety limit. The change of wheel-diameter difference has little effect on the vertical ride quality index of locomotive body. According to the lateral displacement of the locomotive body, the 10 working conditions are divided into three grades. The third grade (working condition 4, working condition 5, working condition 8 and working condition 11) is more conducive to the safe and stable motion of the locomotive. Therefore, in the wheel matching installation and repairing process, priority should be given to the arrangement of wheel-diameter difference of the same locomotive in the third grade. This will provide a reference and basis for the scheme of locomotive wheel economic repairing.

1. Introduction

Under the ideal condition, the wheel-diameter of railway locomotive is the same. But the wheel-diameter difference is affected by machining accuracy, wheel wear and other factors. The wheel-diameter difference not only causes the wheelset to deviate from the track center, but also changes the contact relationship between wheel and rail. When the wheel-diameter difference of the same axle, the same bogie or the same locomotive exceeds a certain limit value, it will have a significant impact on the operation safety, stability and ride quality of the locomotive. At present, regular wheel repairing is the main measure to solve the problem of wheel-diameter difference. But wheel repairing is carried out on the premise of ensuring the diameter difference of coaxial wheel and the same bogie wheel. Therefore, how to arrange the wheel-diameter difference of the same locomotive scientifically and reasonably is studied in depth, which will be helpful to the economic repairing of the locomotive wheel and prolong the service life of the wheel.

Other Many valuable researches were conducted in the field. Zhou [1] analyzed the influence of different factors on the change of wheel-diameter difference and the influence of different wheel-
diameter difference on locomotive. Chi et al. [2, 3] analyzed the force of bogies with different wheel-diameter difference and divided them into three different areas according to the degree of influence. Li et al. [4] studied the influence of wheel shape and wheel-diameter difference on the stability of vehicle system. Han et al. [5] found wheel-diameter difference changed the function of rolling radius difference and wheel-rail contact point, which will affect the running performance of high-speed train. Zhang et al. [6] studied the influence of wheel-diameter difference of different axle on the dynamic performance for a three-axle bogie electric locomotive. Yao et al. [7] studied the influence of wheelset with equivalent in-phase wheel-diameter difference and equivalent reverse phase wheel-diameter difference on the nonlinear critical speed of vehicle. Liu et al. [8] analyzed the influence of the diameter difference of the coaxial wheel on the running performance of the locomotive through the dynamic simulation calculation and the elastic-plastic contact calculation under the dynamic load. Wang [9] studied, analyzed and verified the preventive turning repair strategy of wheel flange wear related to the wheel-diameter difference of the whole vehicle. Li [10] proposed a more scientific and reasonable intermediate maintenance limit for the current wheel-diameter difference maintenance limit of CRH2 EMU. Wang [11] analyzed the relationship between wheel-diameter difference and bearing temperature rise, curve passing, treading and flange failure.

The "wheel-diameter difference" mentioned in the above research is the wheel-diameter difference between the same axle and the bogie, but the research on the influence of the wheel-diameter difference of the same locomotive on the locomotive dynamic performance has not been seen. Therefore, this paper takes the two axle bogie locomotive as the object, establishes the locomotive dynamics analysis model with the SIMPACK software. Based on the research of wheel-diameter difference of the same bogie, 10 special wheel-diameter difference conditions of the same locomotive are put forward. The influence of different conditions and different wheel-diameter difference of the same working condition on the locomotive operation performance is analyzed from the lateral displacement of the car body and the ride quality index of Sperling. At the same time, it also provides reference and basis for making more economic and reasonable locomotive wheelset repairing plan.

2. Establish locomotive dynamics model

2.1. Force analysis of wheel diameter difference

Take the wheel-diameter difference of the same axle as an example and analyze the force of wheelset (only considering the effect of wheel-rail creep force), as shown in Figure 1. The wheelset runs in the negative direction of the x-axis, and the angular velocity of the left and right wheels are equal. When the diameter of the left wheel is larger than the right wheel diameter ($d_L > d_R$), the linear velocity of the left wheel is larger than the right wheel. At this time, the left wheel drives the right wheel to creep forward. The left wheel generates the longitudinal creep force ($F_{Lx}$) along the negative x-axis, and the right wheel generates the longitudinal creep force ($F_{Rx}$) along the positive x-axis. Under the action of creep force, the wheelset produces deflection moment, which causes the wheelset to shake its head clockwise. At the same time, the wheelset produces the lateral creep force ($F_y$) along the positive y-axis, and the wheelset deviates to the right rail. However, with the increase of wheelset displacement, the radius of right wheel contact point gradually increases and exceeds the left wheel contact radius. Then the wheelset shifts to the left. This process is repeated, and the wheelset moves in the shape of a snake. At the same time, the wheelset, bogie and car body as a whole. The shaking motion and lateral motion of wheelset act on the bogie through the suspension force generated by the primary suspension system. And the bogie through the secondary suspension system acts on the car body. When the wheel-diameter difference is large, it may cause the secondary serpentine instability of the bogie or the primary serpentine instability of the vehicle body.

2.2. The model of locomotive dynamics

Taking the locomotive of two axle bogies as the research object, the dynamic analysis model is established by SIMPACK software [12]. Refer to "vehicle system dynamics" [13] for mass, moment of
inertia parameters, suspension system parameters and relevant dimension parameters of all components of locomotive. The locomotive runs on the straight track at the speed of 250km / h, and the lateral and vertical excitation are considered and applied. LM type wearing tread is selected for wheel to match with the rail of 75kg/m. The nominal rolling circle diameter of the wheel is 1250 mm, and the wheel-diameter difference is 0 mm, 0.25 mm, 0.5 mm, 0.75 mm, 1 mm and 1.25 mm respectively. 7 displacement sensors are arranged for the locomotive, and the distribution position is shown in Table 1.

![Figure 1. The stress diagram of wheel set.](image)

| Sensor | Position                                      |
|--------|-----------------------------------------------|
| Vehicle | Vehicle floor 1 m above the center of bogie |
| F-wheelset01 | Front bogie No.1 axle center                |
| F-wheelset02 | Front bogie No.2 axle center                |
| R-wheelset01 | Rear bogie No.1 axle center                |
| R-wheelset02 | Rear bogie No.1 axle center                |

2.3. Working condition of wheel-diameter difference

The difference of rolling circle radius of locomotive wheel determines the stability, ride quality and curving performance of locomotive operation. According to the regulations, the limit of wheel-diameter difference of the same axle ≤ 0.5~1mm, the limit of wheel-diameter difference of the same bogie≤ 2~4mm, and the limit of wheel-diameter difference of the same locomotive ≤ 4~8mm [6]. There are two typical distributions of wheel-diameter difference of the same bogie in the same direction and in the opposite direction [14]. Based on the research of wheel-diameter difference of the same bogie, the following 10 special wheel-diameter difference conditions of the same locomotive are proposed as shown in Figure 2. Figure 2(a) shows that the diameter of eight wheels of an ideal locomotive is exactly the same, Figure 2(b)~2(f) shows the wheel-diameter difference of the front bogie in the same direction, and Figure 2(g)~2(k) shows the reverse wheel-diameter difference of the front bogie.
Figure 2. Different conditions of wheel diameter difference of the same locomotive.

3. The influence of wheel-diameter difference of the same locomotive on the straight running performance of locomotive

For different working conditions and wheel-diameter differences, the straight-line running performance of locomotive is analyzed from lateral displacement and Sperling ride quality index. The lateral displacement refers to the lateral movement of axle center and the vehicle body at the place 1m above the bogie center after the locomotive runs stably. The calculation formula of Sperling ride quality index is as follows [15].

$$ W = 0.896^{10} \sqrt{\frac{a^2}{f}} F(f) $$  \hspace{1cm} (1)

Vertical vibration

$$ F(f) = \begin{cases} 0.325f^2, & f = 0.5~5.9\text{Hz} \\ 400/f^2, & f = 5.9~20\text{Hz} \\ 1, & f > 20\text{Hz} \end{cases} $$  \hspace{1cm} (2)

Lateral vibration

$$ F(f) = \begin{cases} 0.8f^2, & f = 0.5~5.4\text{Hz} \\ 650/f^2, & f = 5.4~26\text{Hz} \\ 1, & f > 26\text{Hz} \end{cases} $$  \hspace{1cm} (3)

Because of the randomness of locomotive vibration, its acceleration and frequency change with time. The vibration signals are grouped according to frequency. Considering the different acceleration values in each frequency segment, the total ride quality index is calculated as follows:

$$ W = \sqrt{W_1^{10} + W_2^{10} + \cdots + W_n^{10}} $$  \hspace{1cm} (4)

3.1. The influence of wheel-diameter difference on locomotive lateral vibration

Taking the wheel-diameter difference of 0.75mm, working condition 4 and working condition 9 as examples, the simulation results are shown in Figure 3 and Figure 4 respectively. In working condition 4, the front and rear bogies adopt the same wheel-diameter difference, but are arranged in reverse direction. In working condition 9, the front bogie adopts the reverse wheel-diameter difference, and the rear bogie adopts the same direction wheel-diameter difference. The process of locomotive from starting to smoothly run, and the lateral vibration coupling superposition of each wheelset is transmitted to the locomotive through the suspension system. When the locomotive runs smoothly, the center of the
wheelset is close to the side with small wheel diameter. At the same time, the vibration phase of the front axle F1 (R1) of the same bogie is ahead of that of the rear axle F2 (R2), which is related to the running direction of the locomotive. The above is consistent with the previous theoretical analysis. As working condition 4 shown in Figure 3, the locomotive has small lateral vibration after 0.73s. After 1.71s of small amplitude vibration, the locomotive runs smoothly and the lateral displacement tends to zero. As working condition 9 shown in Figure 4, the locomotive vibrates slightly laterally from the beginning of operation. After 2.46s, the locomotive runs stably and moves laterally 4.67mm away from the track center. Compared with these two conditions, working condition 4 is more conducive to the smooth operation of the locomotive obviously. The analysis methods of other working conditions are the same, which will not be described in detail.

Figure 3. Lateral vibration of axle and vehicle body under working condition 4.  
Figure 4. Lateral vibration of axle and vehicle body under working condition 9.

Figure 5. The influence of different working conditions on straight-line operation performance of locomotive.

3.2. The influence of wheel-diameter difference on locomotive lateral vibration

Under the same wheel-diameter difference, the influence of different working conditions on straight-line operation performance of locomotive is analysed. As shown in Figure 5, under the same working condition, the larger the wheel-diameter difference is, the larger the lateral displacement after the locomotive run stably. Under different wheel-diameter differences, the lateral displacement of the car body is close to zero under working condition 4, 5, 8 and 11 when the locomotive runs stably. Among
them, working condition 4 and working condition 11 are more conducive to the straight-line running stability of the locomotive. As shown in Figure 6, different wheel-diameter differences have little influence on the vertical ride quality index of locomotive straight-line operation. However, it has a great influence on the lateral ride quality of the locomotive running in a straight line. According to the grading of Sperling ride quality index [15], when the value of W is less than 2.75, the ride quality grade is excellent. Therefore, when the wheel-diameter difference is in the range of 0–1.25 mm, the influence on the locomotive straight-line running stability is not very significant.

![Figure 6](image_url)

**Figure 6.** The influence of different working conditions on straight-line ride quality of locomotive.

![Figure 7](image_url)

**Figure 7.** The influence of different wheel-diameter difference on straight-line operation performance of locomotive under the same working condition.

3.3. **The influence of different wheel-diameter difference on straight-line operation performance of locomotive under the same working condition**

Under the same working condition, the influence of different wheel-diameter difference on the straight-line running performance of locomotive is analysed. As shown in Figure 7, under the same working condition, the lateral displacement of the car body increases with the increase of the wheel-diameter difference after the locomotive runs stably. According to the change range of locomotive lateral displacement, 10 working conditions can be divided into three grades. The first level: the lateral displacement of the car body is 3–8 mm after the locomotive runs stably, which include working
condition 3, 6, 9 and 10. The lateral displacement of the locomotive is greatly affected by the wheel-diameter difference. The second level: the lateral displacement of the car body is 1~3mm after the locomotive runs stably, which include working condition 2 and 7. The lateral displacement of the locomotive is less affected by the wheel-diameter difference. The third level: the lateral displacement of the car body is 0~1mm after the locomotive runs stably, which include working condition 4, 5, 8 and 11. The lateral displacement of the car body is close to 0mm. The increasing trend of lateral displacement of vehicle body under working condition 5 and 8 is relatively obvious, and the change of lateral displacement of vehicle body under working condition 4 and 11 is relatively gentle.

As shown in Figure 8, the influence of different wheel-diameter difference under the same working condition on the lateral ride quality index of locomotive. The change trend of locomotive lateral ride quality index: the first level > the third level > the second level. It is found that the locomotive lateral ride quality index of the second level is less than that of the third level, because the working condition 2 and 7 of the second level belong to the same bogie wheel-diameter difference. The front bogie has the same wheel-diameter difference and the reverse wheel-diameter difference respectively. The rear bogie is in ideal condition: the wheel-diameter difference is zero. And the front and rear bogies of the first and third level have the wheel-diameter difference. Analysis comprehensively shows that the third level (working condition 4, 5, 8 and 11) is more conducive to the straight-line ride quality of the locomotive.

![Figure 8. The influence of different wheel-diameter difference on straight-line ride quality of locomotive under the same working condition.](image)

The above only analyzes the influence of the wheel-diameter difference of the same locomotive on the lateral displacement and locomotive ride quality when the locomotive is running in a straight line. However, the influences of wheel-diameter difference on wheel axle transverse force, derailment coefficient and wheel load reduction rate are similar to that on locomotive ride quality, which will not be discussed in this paper.

4. Conclusions

1) The different arrangement of wheel-diameter difference of the same locomotive has great influence on the lateral vibration of locomotive. With the increase of the wheel-diameter difference, the lateral displacement and the lateral ride quality index of the locomotive tend to increase, but they do not exceed the safety limit. At the same time, the change of wheel-diameter difference has little effect on the vertical ride quality index of locomotive.

2) Putting forward 10 different working conditions of the same locomotive wheel-diameter difference, and divided into three levels according to the lateral displacement of the car body. For the third level, the lateral displacement of car body is close to 0 mm, and the level of lateral ride quality of the car body is excellent. The second level belongs to the category of wheel-diameter difference of the
same bogie. Under the same wheel-diameter difference, the car body lateral displacement of the first level is significantly greater than the third level. At the same time, when the wheel-diameter difference is 0~1.25 mm. Ride quality index, vibration acceleration and other parameters of the locomotive can still meet the requirements of safe and stable operation of the locomotive. Therefore, from the perspective of locomotive safety and ride quality. In the process of wheel pairing installation and repairing, four working conditions of the third level (special working condition 4 and 11) should be given priority. In order to reduce the amount of wheel lathing and prolong its working life.

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