Analysis of Running Stability and Tire Wear of Monorail Vehicles

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Abstract: Based on the movement state of straddle-type monorail vehicle and the force state of wheels, the theoretical model is established, and the dynamic simulation software is used to analyze the anti-overturning stability of guide wheels and stabilizer wheels of straddle-type monorail vehicle under pre-pressure. Three layout schemes of guide wheels and stabilizer wheels are established, and the motion state of straddle-type monorail vehicle under three schemes is compared and analyzed. It is found that the motion state of monorail vehicle is mainly limited by the rolling stiffness and the shaking head stiffness of the vehicle itself. By increasing the rolling stiffness, the roll angle of the vehicle can be reduced, so as to reduce the load variation and speed difference of the running wheels and reduce the wear of the running wheels. Over-increasing the shaking head stiffness can reduce the side slip angle of the running wheels, so as to reduce the side slip of the running wheels and reduce the wear of running wheels.

1. Introduction
As for the increasingly serious urban traffic problems, it is generally recognized that the fundamental solution lies in giving priority to the development of urban public transport system with rail transit as the main part[1-3]. As a short distance and medium and small passenger flow rail transit system, straddle-type monorail transportation system has the characteristics of strong climbing ability, small turning radius, low running noise and low construction cost compared with ordinary wheels-rail transportation system (such as subway, light rail, etc.) [4]. At present, it has become an important mode of rapid rail transit development in large and medium-sized cities, and has been recognized and adopted by more and more cities[5-7].

The running part of straddle type monorail vehicle consists of three wheels, which are walking wheels, guiding wheels and stabilizing wheels, all of which are rubber wheels[8-9]. Among them, the traveling wheels contacts the upper surface of the track beam, bears the vertical load of the vehicle, and transfers the traction force and braking force to the track beam[10-11]. The guide wheels and the stabilizing wheels are all in contact with the side rail of the track beam, wherein the guide wheels not only plays a guiding role, but also ensures the overturning stability of the vehicle movement together with the stabilizing wheels[12]. Vehicle tires not only bear vertical load, traction force and braking force of trains, but also are subjected to lateral force such as centrifugal force and wind force [13-14]. Especially when passing curves, the roll angle and side slip angle between tire and pavement will cause tire treads and shoulders to wear out, which will affect the operation quality of monorail
vehicle\[15\]. In this paper, the stability of the monorail vehicle and the wear condition of the tire are studied through theoretical analysis and simulation calculation.

2. Stress analysis of straddle type monorail vehicle

2.1. Assumption of stress model for straddle type monorail vehicle
In the analysis, the reasonable simplification of the vehicle model is not only easy to understand the basic principles, but also more easily to obtain the analysis results. In this paper, the following assumptions are made when analyzing the force of the straddle type monorail vehicle tire.

- Ignoring the elastic deformation of the car body and bogie frame, that is, the bodywork and bogie frame are rigid bodies.
- The track beam has no initial dip angle, and the torsion deformation of track beam is neglected under loads.
- In the beam section, it is assumed that the force transmitted by the running wheels and the stabilizing wheels to the track beam is perpendicular to the sides of the track beam.

2.2. Force analysis of straddle-type monorail vehicle in operation
In order to ensure that the car body has enough anti overturning stability on the air spring, it is required that the $h_M$ of the car body's buoyancy height should be more than 2m of the body's center of gravity $h_c$, that is, $h_M - h_c > 2g$. Because the lateral span of the straddle type monorail vehicle is very small, the anti roll stiffness of the running tire is relatively small, which makes the vehicle's ability to resist overturning very poor and easy to destabilize. It is an "unstable mode". Therefore, the steering wheel and stabilizing wheel must be set up in the straddle monorail bogie, and the roll resistance moment formed by the combined action of running wheel, steering wheel and stabilizing wheel can ensure the overturning stability of the vehicle. When the guide wheels and the stabilizer contact with the track and set the pre pressure, the height of the buoyant center of the monorail vehicle is greatly improved, and the overturning stability of the monorail vehicle can be guaranteed. The force situation of straddle type monorail vehicle is shown in Figure 1.

![Figure 1. The tire load status of straddle type monorail vehicle (F1 and F2 are traveling wheel load; F3 and F4 are guided wheels load; F5 and F6 are stable wheels load)](image-url)
For two suspension vehicles, the buoyancy height of the vehicle is:

\[ h_M = \frac{8K_{pz}K_{sz}h_1^2b_2^2}{m_c(g(2h_1^2K_{pz} + b_2^2K_{sz}))} \]  

In the formula, \( K_{pz} \) is the vertical suspension stiffness of a system; \( K_{sz} \) is two suspension vertical stiffness; \( m_c \) is car body weight; \( b_1 \) is first suspension of one system suspension; \( b_2 \) is half suspension of second suspension lateral span; \( g \) is gravitational acceleration constant.

Unbalanced centrifugal force for each bogie running on curve is

\[ F_{H_a} = \frac{1}{2} m_c \left( \frac{v^2}{R} - g \cdot \sin(\phi_{cch}) \right) \]  

In the formula, \( \phi_{cch} \) is orbital superelevation angle; \( v \) is vehicle running speed; \( R \) is radius of curve.

Stiffness ratio of guide wheels and stabilizer wheels is

\[ \kappa = \frac{k_g}{k_s} \]  

In the formula, \( k_g \) is vertical stiffness of guide wheels; \( k_s \) is Vertical stiffness of guide wheels.

The Height of the Rotating Center of the Frame from the Rail Surface is

\[ x = \frac{a \cdot \kappa + b}{1 + \kappa} \]  

In the formula, \( a \) is height of guide wheels center gauge rail surface; \( b \) is height of center gauge rail surface of stabilizing wheels.

Transverse displacement of frame is

\[ s_x = \frac{F_{H_a}}{2k_g(\kappa + 1)} \]  

Bogie frame roll angle is

\[ \phi = \frac{M}{2 \cdot k_g \cdot (x - a)^2 + 2 \cdot k_s \cdot (b - x)^2 + 0.5 \cdot k_p^2 \cdot s_p} \]  

In the formula, \( M \) is rolling torque of vehicle produced by lateral force; \( s_p \) is traveling wheels lateral span.

3. Force analysis of steady wheels with or without pre-pressure

3.1. Force state of vehicle with or without pre-pressure of guiding wheels and stabilizing wheels

According to the theoretical calculation, the force analysis of monorail vehicle with or without preload of guide wheels and stabilizer wheels is carried out. When the preload is set to 14 kN, the results of \( F_1, F_2, F_3, F_4, F_5, F_6 \) are obtained as for Table 1.

|                  | \( F_1 \) (kN) | \( F_2 \) (kN) | \( F_3 \) (kN) | \( F_4 \) (kN) | \( F_5 \) (kN) | \( F_6 \) (kN) | Frame tranverse (mm) | Frame roll angle (deg) |
|------------------|---------------|---------------|---------------|---------------|---------------|---------------|----------------------|------------------------|
| Pre pressure     | 59.55         | 20.85         | 5.48          | 22.65         | 18.83         | 9.31          | 9.46                 | 3.41                   |
| Non Pre pressure | 66.03         | 14.72         | 0             | 16.87         | 4.27          | 0             | 20.75                | 4.59                   |
According to Table.1, when the guide wheels and the stabilizer wheels are not pre-stressed, one tyre of the guide wheels and the stabilizer wheels is out of track, and the lateral displacement and roll angle of the vehicle increase significantly, which leads to the increase of the bearing capacity of the running wheels, the guide wheels and the stabilizer wheels. According to the theoretical analysis, the roll stiffness provided by guide wheels and stabilizer wheels is obviously less than that provided by pre-pressure without pre-pressure. Therefore, in order to ensure the safe operation of monorail vehicle on track, it is necessary to set a pre-pressure on guide tire and stabilizer tire so as to make them close to the side of track beam and avoid the guide wheels and stabilizer wheels from leaving track beam. In order to ensure the anti-roll performance of the vehicle, at the same time, excessive pre-pressure will lead to the acceleration of tire wear and the increase of running resistance, so the pre-pressure should be set to a reasonable value.

3.2. Dynamic performance analysis of vehicle with or without pre-pressure of guiding wheels and stabilizing wheels

The dynamic model of monorail vehicle is established by using the dynamic analysis software SIMPACK. The working condition of monorail vehicle passing through a curve under or without preload is simulated, and the motion state of monorail vehicle is analyzed. The simulation results are shown in Figure.2 (a) ~ (d).

The results of vehicle dynamics simulation with or without preload of steering wheels and stabilizer wheels show that: (1) with Pre pressure, car body transverse motion, car body roll, bogie transverse motion and bogie roll are smaller; (2) without Pre pressure, car body transverse motion, car body roll, bogie transverse motion and bogie roll go through a long time when entering circular curve and straight line compared with Pre pressure. Only after vibration can it be restored to a stable state.
Therefore, it can be concluded that when the pre-pressure is set on the guide wheels and the stabilizer wheels, the deviation and vibration of the car body will be improved a lot, and the vehicle has good anti-overturning stability.

4. Dynamic performance analysis of three kinds of stable wheels arrangement schemes

According to the design requirements, one or two stabilizing wheels can be set on each side of the bogie. The following three schemes of stabilizing wheels are analyzed. Among them, the vertical spans of the three schemes are the same; the first and second schemes are two stable wheels on each side of the bogie, but the vertical spans of the stable wheelbase rail surface are different; the second and third schemes are two stable wheels and one stable wheel on each side of the bogie, respectively, but the vertical spans of the stable wheelbase rail surface are the same.

![Diagram of three stable wheels arrangement schemes](image)

Figure 3. Three stable wheels arrangement scheme

4.1. Effect of pre-pressure on vehicle performance

The effects of three schemes on vehicle performance under different pressures are calculated. The calculation results are shown in Figure 4.

![Graph showing effect of pre-pressure on guiding force and frame roll angle](image)

Figure 4. Effect of pre-pressure on guiding force and frame roll angle

It can be seen from the calculation that with the increase of the preload, the change of the guiding force and the roll angle of the frame gradually tend to be flat after the logarithmic trend decreases. In order to improve the service life of tires, it is necessary to maintain the normal deformation of tires under the condition of rated pressure and load, and to minimize the change of tire load so as to reduce the dynamic deflection. Considering vehicle performance and tire life, the pressures of guide wheels and stabilizer wheels are 14 kN.

4.2. Dynamic performance analysis of three vehicle schemes

The motion state of three monorail vehicle schemes is simulated and calculated by the dynamic simulation software SIMPACK,. The calculation results are shown in Figure 5.
The simulation results show that: (1) the roll moment provided by the stabilizer wheels is different among the three schemes, and the smaller the roll moment provided by the stabilizer wheels is, the larger the roll angle is; (2) Because the shaking head stiffness provided by the guide wheels and the stabilizer wheels in scheme 1 and scheme 2 is the same, the frame shaking head angle and the body shaking head angle of scheme 1 and scheme 2 are the same, and the three stabilizer wheels in scheme 1 and scheme 2 do not provide the shaking head stiffness, because the three stabilizers in scheme 1 and scheme 2 In the third scheme, the shaking angle of the frame and the car body are larger.

4.3. Stress analysis of tyres with three stable wheels arrangements

The wheel tyre forces under three kinds of stable wheels arrangement schemes are analyzed, and the vertical force of the traveling wheels, the variation of the guiding force of the guide wheels, the variation of the guiding force of the stabilized wheels and the sideslip angle of the traveling wheels under the three schemes are obtained.
From the simulation results, it can be seen that the change of the vertical force of the running wheels in the three schemes is consistent with the change of the roll angle of the frame, which is mainly determined by the rolling stiffness of the vehicle; the change of the bearing capacity of the guide wheels and the stabilizer wheels in scheme 2 is the smallest, and the change of the bearing capacity of the guide wheels and the stabilizer wheels in scheme 3 is greater than scheme 1, mainly because the stabilizer wheels of scheme 3 do not bear the guiding force, bears only by the guide wheels, and the vertical span of the stabilizer wheels in scheme 3 is larger than scheme 1. The change of the side slip angle of the running wheels is consistent with that of the shaking angle of the frame, which is mainly determined by the shaking stiffness of the guide wheels and the stabilizer wheels.

From the above analysis, it can be seen that the dynamic performance of the monorail vehicle is mainly determined by the roll stiffness and shaking head stiffness of the vehicle itself after reasonable setting of the guide tire and stable tire preload. By increasing the roll stiffness, the roll angle of the vehicle can be reduced, thus the load variation and speed difference of the running wheels can be reduced, and the wear of the running wheels can be effectively reduced; by increasing the rocker stiffness, the wear of the running wheels can be reduced. The side slip angle of the small running wheels can reduce the side slip of the running wheels and the wear of the running wheels effectively. From the structure of the three schemes, two stabilizing wheels on each side can provide greater roll stiffness and shaking head stiffness under the same track beam; one stabilizing wheel on each side can improve roll stiffness by increasing the vertical span of the stabilizing wheels; the rotation center of the frame is closer to the guide wheels, which makes the bearing capacity of the stabilizing wheels change greatly, and because the stabilizing wheels is arranged in rotation. Longitudinal center of the girder basically does not provide the shaking head stiffness, which should be borne by the guide wheels.

5. Conclusion
Firstly, the force analysis of the stabilizing wheels and the guiding wheels of straddling monorail vehicle is carried out, then the dynamic performance of the vehicle is simulated when the guiding
wheels and the stabilizing wheels have preload or not. Finally, the dynamic performance of the vehicle and the force of the tire under the three schemes of the stabilizing wheels arrangement are compared and analyzed, and the results are obtained.

1. When the guide wheels and the stabilizer wheels have pre-pressure and are not off the rail surface, they can provide larger roll stiffness and effectively improve the operation safety of the monorail vehicle.

2. Pre-pressure setting can improve the roll performance of vehicles, but too large setting will lead to accelerated tire wear and increase running resistance. Therefore, reasonable pre-pressure setting should be combined with the rated load of tires and other conditions.

3. The rolling stiffness and shaking head stiffness of the vehicle can be improved by arranging the guide wheels and the stabilizer wheels reasonably, so as to reduce the roll and sideslip of the running wheels, and the roll of the guide wheels and the stabilizer wheels, so as to reduce the tire wear.

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