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Analysis on Steering Capability of a New Bogie with Independently Rotating Wheels

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Abstract

A new scheme about a coupled bogie with Independently Rotating Wheels was put forward firstly. And then it is fund by theoretic analysis that the bogie takes on prominent radial capability on curved track and splendiferous restoring capability on tangent track. Lastly, a dynamic calculating model of the coupled bogie with independently rotating wheels has been established and a dynamic simulation analysis on steering capability of the bogie was made and the simulation results can inosculate foregoing theoretic analysis, which illuminates that the coupled bogie can solve drastically the difficulty about steering problem of independently rotating wheel.

Keywords **:** *Independently rotating wheel, Coupled bogie, Steering capability*

1. Introduction

As the independently rotating wheels(is shortly called as IRW) can individually rotate around its axle while the axle itself does not rotate, so its axle can be made into cranked axle and thus the floor height of the vehicle can be lowered, therefore the IRW are generally adopted in low-floor light rail vehicles. As known, IRW can't generate longitudinal creep forces that play a key role in the steering capability, so IRW has a poor steering capability. On the tangent track, the IRW usually drift to one side of the track and can't restore to the center of the track, and on the curved track, the IRW have larger attack angle, which usually causes the flange contact rail. Therefore, the IRW not only cause serious wheel-rail wear but also increase the risk of derailment.

The steering problem is a barrier for the development of IRW, in order to solve this problem, a lot of solutions has been put forward [1]. The initial solution is to design the special wheel tread [2-3], which increase the contact angle difference of left and right wheels, and the gravity restoring force can be increased, which can make the wheelsets restored, whereas this scheme can not let the IRW automatically tend to the radical position on the curved track. So some radical mechanisms have been put forward, for instance, the Talgo train in Spain had successfully applied forced steering mechanism for the single-axle bogie with IRW [4]. However the forced steering mechanism applied to the two-axle bogie with IRW does not work perfectly [5], because the reasonable steering gain coefficient can't easily be obtained in the intricate condition of track. Japanese developed a radical bogie that adjusts the wheelsets to the radical position by centrifugal force[6]. But its effect will be limited by the external condition such as curve radius, superelevation and the running velocity. The Professor Frederich in Germany has developed a bogie (Einelrad-Einelfahrwerk, is shortly called as EEF) [7-8], which relay on the gravity to regulate the yaw angle of IRW. Yet the bogie has too complicated structure and the cost of the manufacture become higher.

Up to now, the application of IRW isn't satisfying, so a coupled bogie with IRW has been put forward in this paper.

2. Steering Principle of the New Bogie

The sketch map of the coupled bogie with IRW is shown in Fig. 1, the bogie is made up of two single-axle bogies linked by a flexible coupled mechanism, so it is also called as the flexible coupled bogie with IRW.

The steering capability of a bogie includes the radial capability on curved track and the restoring capability on

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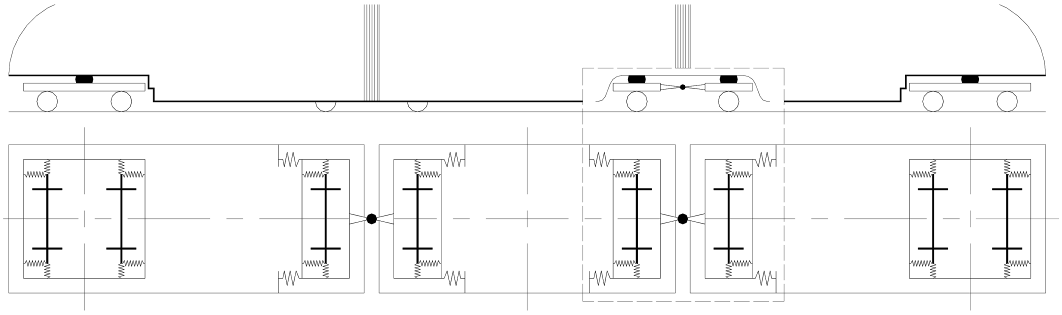
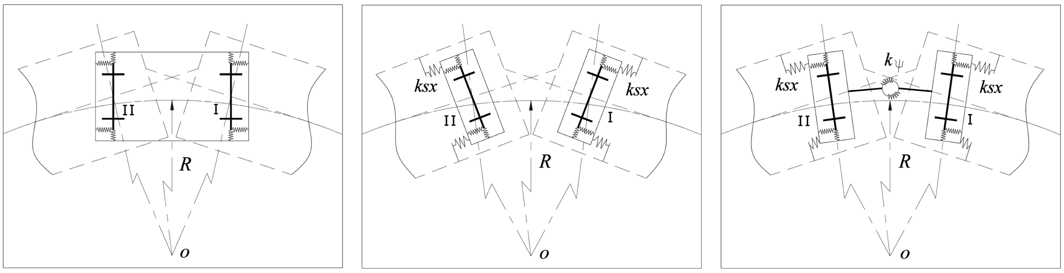


Fig. 1 Sketch of a coupled bogie with IRW



(a) Two-axle bogie (b) Single-axle bogie (c) Flexible coupled bogie

Fig. 2 Radial capability of the three types of bogie with IRW on curved track

tangent track. The radial capability is mainly embodied in whether the attack angle can tend to zero on the curved track and the restoring capability is embodied in whether the lateral displacement of the wheelsets departuring the centre of track can restore to zero on the tangent track.

In the lateral and yaw motion equations of coupled bogie, the primary suspension stiffness of single-axle bogie is far greater than its secondary suspension stiffness, so in theoretical analysis, the frame and the wheelsets can be considered as a whole and the motion equations of bogie can be written as follows.

Lateral motion equation:

$$M_B(\ddot{y}_{Bi}+V^2/R_{Bi}+\ddot{h}\phi_{seBi}) = T_{wyi}+F_{gyi}+F_{syi}+M_B g\phi_{seB} \qquad (1)$$

Yaw motion equation:

$$I_{Bz}\left[\ddot{\psi}_{Bi}+V\frac{d}{dt}\left(\frac{1}{R_{Bi}}\right)\right]=M_{wzi}+M_{szi}+M_{czi} \qquad (2)$$

Where: i=1, 2, 3, 4; is M_B the mass of the single-axle bogie; I_{BZ} is the yaw inertia of single-axle bogie; y_{Bi} is the lateral displacement of single-axle bogie; ψ_{Bi} is the yaw angle of single-axle bogie; v is the vehicle running speed; R_{Bi} is the radius of curved track; φ_{seBi} is the superelevation angle of the actual track; h is the distance between mass center of bogie and rail surface; T_{wyi} is the lateral creep force of wheelset; F_{gyi} is the gravity restoring force of wheelset; F_{syi} is the lateral force of secondary suspension; M_{wzi} is the yaw deflection torque produced by the wheel-rail forces; M_{szi} is the yaw deflection torque produced by secondary suspension forces; M_{czi} is the yaw deflection torque produced by flexible coupled mechanism.

In this paper, the coupling mechanism in coupled bogie only supply the stiffness of yaw angle for the leading and trailing single-axle bogie and not interfere other motions, so the role of coupling mechanism is only embodied in yaw motion equation. When the coupling moment M_{czi}=0, the coupled bogie evolved into two single-axle bogie with IRW, and when the coupling moment M_{czi} is given a very big value, the coupled bogie can approximately simulate two-axle bogie with IRW, thus single-axle bogie and two-axle bogie are only two extreme forms of the coupled bogie.

2.1 The Analysis of Radial Capability on Curve Track

According to the comparison of fig. 2, the radial capability of the flexible coupled bogie with IRW can be intuitively understood.

Fig. 2(a) shows the radial capability of two-axle bogie with IRW on a curved track. Since wheelsets I and II are constrained by the same frame, so the wheelset I has a positive attack angle and wheelset II has a negative attack angle, which indicates that the wheelsets I and II can not outspread enough to achieve the radial position on the curved track.

Fig. 2 (b) shows the radial capability of single-axle bogie with IRW on a curve track. Since the wheelsets I and II are not constrained by the same frame but by their respective car bodies, so the wheelset I has a negative attack angle and wheelset II has a positive attack angle, which indicates that the Wheelsets outspread too much to achieve the radial position on the curved track.

By further analysis, it is known that the reason why the front and rear wheelsets of the two-axle bogie can not outspread enough to achieve the radial position on the curved track is that the constrain on wheelsets applied by the rigid frame is too great, while that of the two single-axle bogies outspread too much to achieve the radial position on the curved track is the absence of some necessary constrain between the two wheelsets. However the flexible coupled bogie can make up for the drawbacks of the former two types of bogies. When a appropriate coupling stiffness for the coupled bogie is chosen, the Wheelsets would advisably outspread to achieve the perfect radial position on the curved track(showed in Fig. 2(c)), which is just the intention of the flexible coupled bogie with IRW put forward in this paper.

When a train steady-state running on curved track, the left side of the equation (2) is equal to zero, while on the right side of the equation, the yaw deflection torque M_{wzi} which mainly generated by the longitudinal creep force is very small and it can be ignored. So the equation (2) can be written into:

$$M_{czi}+M_{szi}=0 \tag{3}$$

$$M_{szi}=-2k_{sx}b_s^2\left[\psi_{Bi}-\psi_c+(-1)^i\frac{l}{R}\right] \tag{4}$$

$$M_{czi}=(-1)^i k_\psi\left[(-1)^{i+1}\psi_{Bi}-(-1)^{i+1}\psi_{B(i\pm1)}+\frac{2b}{R}\right] \tag{5}$$

Where: i= 1, 2; k_{sx} denotes the one side secondary suspension longitudinal stiffness; K_ψ is the yaw angle stiffness due to the coupled mechanism; b_s is half of the secondary suspension lateral span; b_c is half of the coupled mechanism lateral span; l is half of the nominal distance between front and back bogies centers; b is half of the coupled bogie wheelbase; R is the radius of the circle curve; ψ_B is the yaw angle of bogie; ψ_c is the yaw angle of car body.

Considering the displacement of the wheelsets and the deformation of the suspensions system are far shorter than the length of the nominal distance between front and back bogies centers $2l$, thus the central part of the car body is approximately tangential with the circle curve, i.e. $\psi_c\approx0$. When a train steady-state running on a circle curve track, in order to let the front and rear wheelsets of the coupled bogies achieve radial position completely, must have $\psi_{Bi}=\psi_{B(i+1)}=0$. So according to equations (3)~(5), we can obtain:

$$k_\psi\frac{2b}{R}=2k_{sx}b_s^2\frac{l}{R} \tag{6}$$

Reduces to

$$k_\psi=b_s^2\frac{l}{b}k_{sx} \tag{7}$$

It is known from the equation (7) that the coupling stiffness k_ψ is only relational with the inherent configuration parameters (such as l, b, b_s, b_c) of the train system and the secondary suspension longitudinal stiffness k_{sx}, yet irrespective to the external condition parameters(such as speed of the train and curve radius of the track), which means that as long as the coupling stiffness k_ψ is selected according to equation (7), whatever external condition(curve radius and speed)change, the leading and trailing wheelsets of the coupled bogie can run automatically to radial position by the coordinated operation of the flexible coupled mechanism and the secondary suspension systems of the vehicle. So the coupled bogie is also called as the self-acting radial bogie with IRW.

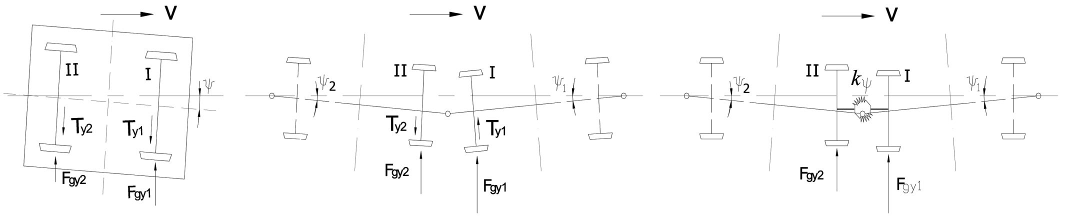
2.2 The Analysis of Restoring Capability on Tangent Track

When the train runs on tangent track, equation (1) will be simplified as:

$$M_B\ddot{y}_{Bi}=T_{wyi}+F_{gyi}+F_{syi} \tag{8}$$

In equation (8), if the resultant force of right side has the opposite direction to the lateral displacement y_{Bi}, the wheelsets can restore. The direction of gravity restoring force F_{gyi} is always opposite to the lateral displacement y_{bi}. The lateral creep force T_{wyi} is related to the yaw angle of wheelset and its phase is usually asynchrony to the lateral displacement y_{Bi}. The lateral suspension force F_{syi} related to suspension stroke can't be controlled artificially. So the gravity restoring force and lateral creep force will usually be changed to make the wheelset restored. There are three measures as follows:

(1) Increasing the gravity restoring force F_{gyi} to make the resultant force has the opposite direction to the lateral displacement y_{Bi}. The measurement mainly relies on increas-



(a) Two-axle bogie (b) Single-axle bogie (c) Flexible coupled bogie

Fig. 3 Restoring capability of three kinds of bogies on tangent track

ing the contact angle difference of wheelsets and the tread have to be designed specially.

(2) Reducing the lateral creep force T_{wyi} to make the resultant force has the opposite direction to the lateral displacement y_{Bi}. This measurement mainly relies on adding radial mechanism to make the yaw angle of wheelsets approach to zero.

(3) Changing the direction of the lateral creep force T_{wyi} to make the lateral creep force T_{wyi} has the opposite direction to the lateral displacement, which will make the wheelset restore promptly. But the measurement can only be achieved in some special bogie with special mechanism.

Theoretically, the measurement (2) is the best of the three because the radical measures can not only make the wheelsets restore but also reduce the wheel-rail wear. Actually this is the development tendency of IRW and the new coupled bogie put forward in this paper also uses this theory to make the IRW restore.

Fig. 3 shows restoring capability of three kinds of bogies on tangent track. Fig. 3 (a) shows the restoring capability of two-bogie with IRW on tangent track. When the wheelset I runs to the right ride of the track, at the action of the gravity restoring force, the wheelset I will have the tendency to restore to the centre of the track, at the same time due to the influence of the suspension system, the frame will generate a positive yaw angle, which will make the wheelset I and II also produce a positive yaw angle that will make wheelset I and II produce positive lateral creep force. Because of the influence of lateral creep force, wheelset I will be prevented from restoring to restore to the centre of the track, thus when the lateral creep force and the gravity restoring force reach balance, wheelset I and II will stay at that position and can not restore to the centre of the track.

Fig. 3 (b) shows the restoring capability of single-axle bogie with IRW on tangent track. Since each wheelset has its own frame, and there isn't any connection between wheelset I and II, they are only constrained by their own car body. When wheelset I runs to the right side of the track, the front car body will generates a negative yaw angle because of the influence of suspend system. Since the front and rear car bodies are jointed together, the rear car body will generate a positive yaw angle. In this case, the front car body will compel the wheelset I to generate a negative yaw angle ψ_1 that will make wheelset I produce a negative lateral creep force. The lateral creep force and the gravity restoring force have the same direction, which will make the wheelset I restore to the centre of the track. At last the wheelset II will also restore to the centre of the track.

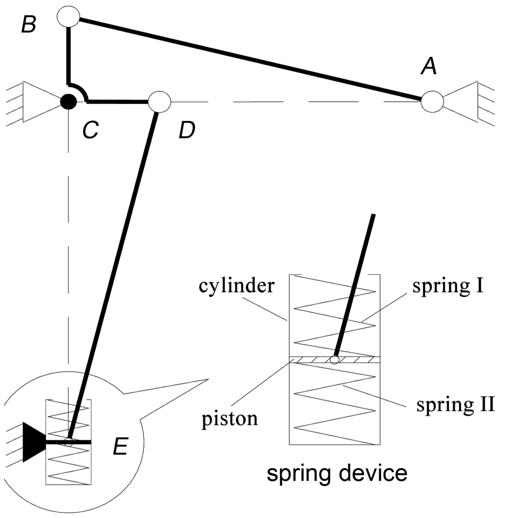


Fig. 4 The sketch of coupling mechanism Fig. 5 The assembling drawing of coupling mechanism

As for the coupled bogie with IRW, because of the cooperation action of suspend system and flexible coupling mechanism, wheelset I and II can automatically adjust the yaw angle near to zero which can decrease the lateral creep force of wheelsets. In this case, the gravity restoring force will play a key role in lateral wheel-rail force and it will make the wheelsets quickly restore to the centre of the track, just as Fig. 3(c).

3. The Design of Flexible Coupling Mechanism

Fig. 4 shows the sketch of the flexible coupling mecha-

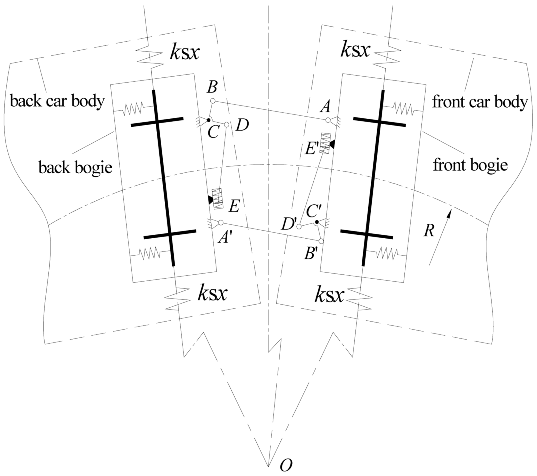


Fig. 5 The assembling drawing of coupling mechanism

nism, which is composed of crank BCD, connecting rods AB and DE, and spring device which consists of cylinder, piston, spring I and spring II.

The assembling drawing of coupling mechanism is shown in Fig. 5. The point C of crank BCD is jointed on the rear bogie. The end A of connecting rod AB is jointed on front bogie and end B is jointed to the point B of crank BCD. The end E of connecting rod DE is jointed on piston and the end D is jointed to the point D of crank BCD. The cylinder of spring device is fixed on the rear bogie. The other mechanism is symmetrically assembled on the bogie.

The BC and CD of crank BCD have the same length. The length of connecting rod AB is equal to that of the rod DE, and the distances between A and C is equal to that between C and E. Thus the longitudinal distance between the front and rear bogies will be transformed into the equal lateral distance by the coupling mechanism. Since the connecting rod AB has greater length and its two ends are jointed by spherical hinge, so its equivalent lateral and longitudinal stiffness are very small and can be ignored, witch just can meet the assumption in the foregoing theoretical analysis.

4. Simulation Results

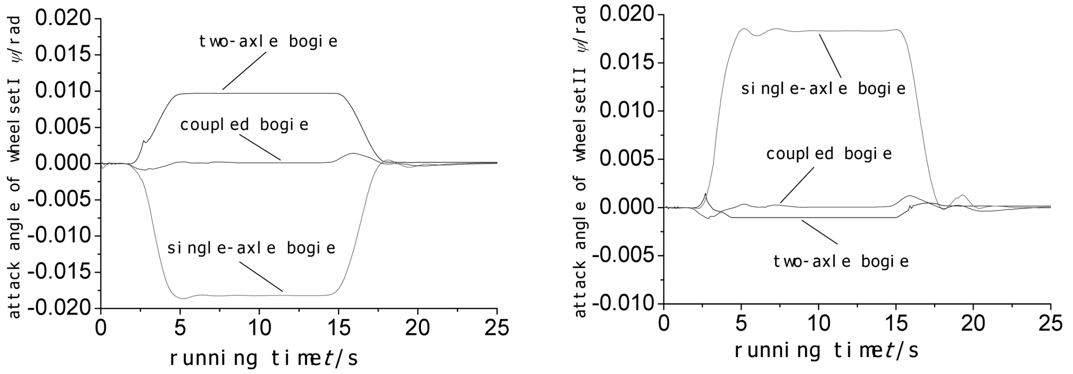
In the above section, the steering characteristic of the coupled bogie with IRW is only obtained by theoretical derivation under some assumptions. Then in this section, the steering characteristic of the coupled bogie will be validated by computer simulation.

In this paper, the multi-body system dynamics software SIMPACK is used for dynamic modeling and simulation analysis. As shown in Fig. 1, the model consists of three car bodies (they are articulated each other in turn) and four bogies(the two bogies locating the ends of train are conventional two-axle bogies and the two bogies in the middle of train are coupled bogies with IRW). The coupling stiffness k_ψ is chosen according to the equation (7).

4.1 Simulation Analysis of Radial Capability on Curved Track

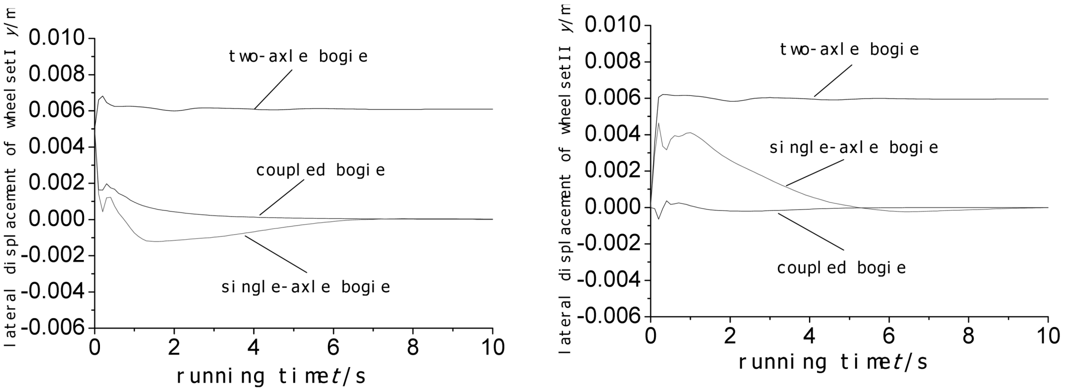
In simulation, two-axle bogie, one-axle bogie and the coupled bogie are all running on a R200m curved track at the speed of 40 km/h.

Fig. 6 shows the attack angles comparison results of three types of bogie running on a curved track. It can be seen that the attack angle of the front wheelset of two-axle bogie is positive and that of the rear wheelset is negative, and the attack angle of the front single-axle bogie is negative and that of the rear single-axle bogie is positive, which is just opposite to that of the two-axle bogie, as for the flexible coupled bogie with IRW, the attack angles of the front and rear wheelsets are both nearly equal to zero,



(a) Attack angle of wheelset I (b) Attack angle of wheelset II

Fig. 6 Comparison of the steering performance on curved track



(a) lateral displacement of wheelset Ⅰ (b) lateral displacement of wheelset Ⅱ

Fig. 7 Comparison of the restoring capability on tangent track

which indicates that the coupled bogie has the prominent radial capability on curved track.

4.2 Simulation of Restoring Capability on Tangent Track

In simulation, two-axle bogie, one-axle bogie and the coupled bogie are all running on tangent track and given a same initial disturbance.

From the Fig. 7, it can be seen that the wheelsets I and II of two-axle bogie with IRW keep balance at one side of the track and can not restore to the centre of the track, and the wheelsets I and II of single-axle bogie with IRW can slowly restore to the centre of the track, whereas the wheelsets I and II of the coupled bogie can quickly restore to centre of the track. This phenomenon indicates that the coupled bogie with IRW has the splendiferous restoring capability on tangent track.

5. Conclusion

From these analyses all above on the coupled bogie with IRW, it can be concluded as follows:

(1) On curved track, the coupled bogie has the prominent radial capability.

(2) On tangent track, the coupled bogie has the splendiferous restoring capability.

(3) Contrast the coupled bogie with the two-axle and single-axle bogie, the steering capability of the coupled bogie with IRW possess prominent dominance of the three bogies, which says that the coupled bogie with IRW has huge exploitation potential.

Acknowledgments

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