Weihua MA, Rongrong SONG

Southwest Jiaotong University

Analyses of the Additional Stiffness Function of the Traction Bar on the Vertical Dynamics Performance of Subway Vehicle

***Abstract**. This paper analyses the influence of the additional stiffness function of the traction bar on the vehicle vertical dynamic performance. Based on the subway vehicle dynamics model, the influences of the additional stiffness function of the traction bar on vehicle's response to vertical impact, carbody vertical ride index and relevant phenomena of wheelset longitudinal vibration resonance were analyzed. Results indicate that the additional stiffness function of the traction bar will increase the stiffness of the secondary suspension system. It not only increase the response of the vehicle to vertical impact and reduces the ride comfort of vehicle, but also increase the vertical and longitudinal vibration acceleration, and the vertical dynamic load of the first and secondary suspension increased too. Put forward that the vertical dynamic performance of the vehicle can be improved through decrease the connection stiffness of the traction bar to 25% of the present value.*

***Streszczenie.** W pracy nalizowano wpływ dodatkowej funkcji sztywności trakcyjnej belki na poziome dynamiczne właściwości pojazdu podziemnego. Rezultaty analizy pokazały że sztywność belki trakcyjnej zwiększa sztywność systemu zawieszenia. Może to zwiększać wibracje poziome pojazdu. (**Analiza funkcji sztywności belki trakcyjnej na właściwości dynamiczne pojazdu podziemnego**).*

Keywords: Wheel Wear; Wheel Out-of-Round; Vertical Impact; Dynamic Performance; Subway Vehicle
Słowa kluczowe: właściwości dtynamiczne, sztywność, pojazd podziemny.

Introduction

The traction bar system plays an important role during the running of the railway vehicle, especially in traction and braking condition [1][2]. The additional stiffness function will form if the traction bar has short length and big stiffness. As it increase the stiffness of the secondary suspension of the vehicle, it will lead many abnormal phenomena of the vehicle, such as wheel wear, wheel out-of-roundness and the deterioration of riding comfort. For the reason that the additional stiffness function of the traction bar not easy formed, it seldom lead enough attention of people, let alone solve wheel wear and dynamics performance worsen problem of the vehicle from the point of view of traction bar [3][4].

Wheel wear and wheel out-of-roundness phenomenon were common existed in railway vehicles. A number of studies regarding wheel wear especially wheel out-of-roundness have been performed, most of which concern the influence of wheel/rail contact geometry, material and track quality or reduce the wheel wear problem by adopt improved wheel profile [5][6].

Kreuzen describes the phenomenon of wheel polygonization existing in Netherlands railway, similar phenomenon also presents in Germany and France [7]. An extensive measurement campaign was launched in order to obtain a representative indication of wheel Out-of-round existing in current traffic in Sweden in 2002. 99 randomly selected railway wheels which had traveled a distance of more than 100000 km were investigated, both tread and disc braked wheels were measured. Based on it, wheel irregularities around the complete wheel circumference and the change in transverse profile due to wear and plastic deformation were studied [8][9].

Above research mainly focus on the wheel wear or wheel out-of-round itself, less relation it with the vehicle dynamics performance directly. During the last decades, a number of papers present investigations on the vertical dynamic performance of railway vehicles, and put forward many methods to improve the vertical dynamic performance [10][11]. To reduce the vertical bending vibration of railway vehicle carbody, various countermeasures have been proposed, among which reference [12] focuses upon the interaction between carbody vertical bending and bogie longitudinal motion, and presents a theory to utilize the longitudinal vibration in bogies as a dynamic vibration absorber, then numerical and experimental studies to verify the theory using Shinkansen vehicles are described. Carbody vertical vibration also can be leaded by wheel set longitudinal vibration, in addition, wheelset longitudinal vibration resonance not only can deterioration the riding comfort of the carbody, but also can worsen the wheel tread wear and wheel tread spalling [13]. Except the structure and suspension parameters, other equipped device also can lead the vertical vibration of the carbody. One kind of locomotive equipped with self-steering bogie once occur abnormal vertical vibration during the line test, and Luo et al confirmed that the problem is caused by the arrangement of braking unit which amounted on steering beam [14].

Although so many researches focus on wheel wear and vehicle vertical dynamics performance problem respectively, few papers concern the relationship between wheel wear and the deterioration of vehicle vertical dynamics performance, and not consider the additional stiffness function of the traction bar in the dynamics model. This paper put forward that the additional stiffness function of the traction bar is one of the most important source of the wheel wear and the vertical dynamics performance worsen phenomenon. One kind of subway vehicle of China has serious wheel wear problem for the reason of additional stiffness function of the traction bar, and the wheel wear rate is about 1.25mm/10000km, while the common value of such vehicle is 0.10mm/10000km [15]. It presents much grade spalling on the intersection zone between wheel tread and flange just after new subway vehicle has a short period running on the line, then it leads to the phenomenon of wheel out-of-roundness. As a result, the vertical and longitudinal vibration acceleration of the carbody turns big and causes the deterioration of riding comfort. To points out that the ride index of the subway vehicle turns worse even if the wheel out-of-roundness amplitude exceeds 0.25mm. The track polish and wheel re-profiling method only have a short term effect, and cannot solve this problem. Further more, investigation results show that both the primary suspension spring broke and anti-roll bar joint damage phenomenon exit in the subway vehicles, and the brake system of the vehicle also not the main reason. To solve this problem, the subway vehicle dynamics model which considers the additional stiffness function of the traction bar was setup and the influence of the additional stiffness function of the traction bar on the dynamics performance of the subway vehicle were analyzed in this paper. According to the simulation results of this paper, one of the important sources which cause above phenomenon is the additional stiffness function of the traction bar.

It is organized as follows: the bogie structure and the dynamics model of the subway vehicle is described in Section 2; Section 3 demonstrates the additional stiffness function of the traction bar system; Section 4 presents the dynamic simulation results of the additional stiffness to the vehicle; Section 5 put forward one kind of improve method to solve this problem.

Model

The bogie structure of the subway vehicle shows in Figure 1. The bogie consists of two wheelsets, one bogie frame, four journal boxes, the primary suspension system, the secondary suspension system, one traction bar system, and other attachment settings. The primary suspension of the bogie consists of cone metal rubber spring with appropriate vertical and lateral stiffness. The secondary suspension made up of air spring with big flexibility, lateral damper, vertical damper, and anti-roll bar settings.

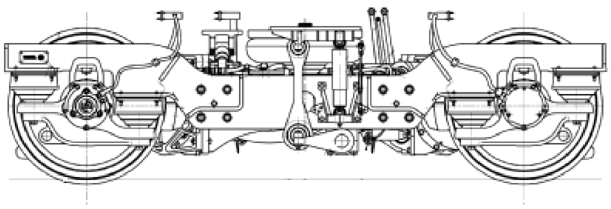


Fig. 1. The bogie structure system

Single traction bar with the length of 0.58m is adopted on the subway vehicle (Figure 2). The traction bar system is characterized with short length and high stiffness (> 2×107N/m).

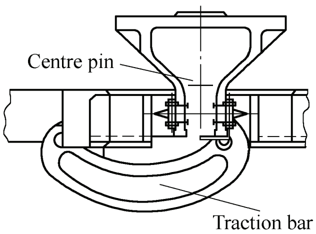


Fig. 2. The traction bar system

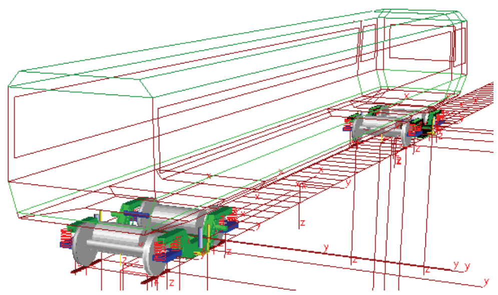


Fig. 3. Dynamics model of the subway vehicle

Based on the structure and suspension parameters of the subway vehicle, the dynamics model is setup by the dynamics simulation software SIMPACK [16]. The wheel profile adopted by the subway vehicle to match with 60kg/m weight rail is GMC type profile, and the cant of rail is 1/40. The traction bar is considered as an independent body in the model. One end of the traction bar is articulated with carbody, and the other end is connected with the bogie by the force element. The subway vehicle dynamics model shows in Figure 3 and the detail parameters of the subway vehicle can be found in reference [15].

Additional Stiffness Function of the Traction Bar System

As the existing of primary and secondary suspension system, the vertical track impact should not transfer to the carbody directly. However, the vertical vibration of carbody turns big when it has a small wheel out-of-roundness. It seems that the vehicle doesn’t have the secondary suspension, or the secondary suspension does not work properly. According to the experience, the anti-roll bar settings and the traction bar system may lead such phenomenon. As the design of the anti-roll bar is mature and it is widely used at many vehicles successfully. Therefore, it may be something wrong with the traction bar system and it leads the secondary suspension systems lose damping function.

There is a relative motion in both lateral and vertical directions between carbody and bogie (mainly happens on curve, switch, up/down slope or track junction et al.). Traction bar should compensate the movement of the bogie with respect to the carbody on both lateral and vertical direction, or else it would produce additional constraint and increase suspension stiffness. Generally speaking, when it is adopted on the locomotive, a single traction bar’s length is no less than 1.6m with large volume rubber joints at the end of the bar to improve its bearing capacity and alleviate the impact [17][18]. With regard to single traction bar, the length and connection stiffness are the two key parameters in design, which are correlated with each other to fulfill the traction function and the movement of the bogie with respect to the carbody together. Therefore, the swing angle of short traction bar is bigger than that of the long one when it has the same relative motion between carbody and bogie.

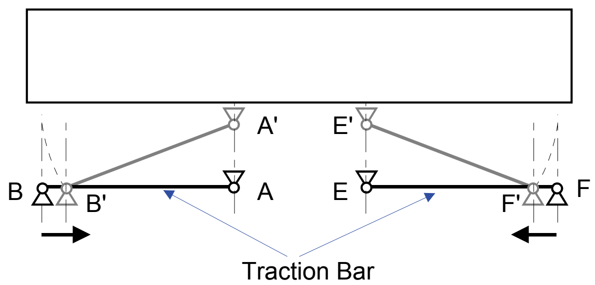


Fig. 4. The Traction bar constraint to vehicle motion

It can be seen from Figure 4 that if there is a relative motion in vertical or lateral direction between carbody and bogie, it has to be compensated by the approach of front and rear bogies by B to B’ and F to F’, for the reason that the two connection points on the carbody A and E can not move comparatively. When vehicle is running with constant speed, it’s easy to realize this compensation for the small rolling resistance of wheel set. However, when the vehicle is in traction/braking condition, the wheel sets are constrained by the track, so as to the relative position of the front and rear bogies are difficulty to change. It means that the carbody can’t have bounce or lateral motion with respect to the bogies easily for the additional stiffness function of the traction bar, even the stiffness of air spring is smaller. It equals to the increase of the stiffness of the secondary suspension in some degree.

Therefore, the result of the additional stiffness function of the traction bar is equivalent to increase the vertical stiffness of the air spring. It will lead to the appearance of several following phenomena:

——Increasing the vertical acceleration of the carbody;

——Increasing the load of primary suspension system;

——Lead the happen of serious wheel wear.

Simulation Results

Response of Vertical Impact

In order to simulate the subway vehicle's response to vertical impact, calculations are made in the case that the subway vehicle runs over triangle pitch during braking. From it can see the influence of the additional stiffness function of the traction bar to the carbody response of vertical impact. Generally speaking, the braking deceleration of subway vehicle is about 0.8~1.0m/s2. Assuming that the braking deceleration is 1.0m/s2, on condition of which the vehicle's response analysis is done when running over a triangle pitch. The maximum depth of the triangle pitch is set 10.0mm with the length of 5.0m. Let the vehicle runs over the triangle pitch with an average speed of 50km/h. The following three cases are chosen for comparison:

Case1: Existing vehicle with braking deceleration of 1.0m/s2

Case2: Existing vehicle with braking deceleration of 1.0m/s2, without consideration of traction bar settings

Case3: Existing vehicle, and coasting running without braking deceleration

The vibration acceleration result of the front test point of the subway vehicle shows in Figure 5. It can be seen from the figures that the vertical vibration response in the triangle pitch with similar value between case 2 and 3, and the response of case 1 in the triangle pitch is obviously higher than the other two cases. The carbody vertical acceleration reached a peak when the subway vehicle passes the triangle pitch. The maximum value of case 1 is 0.9m/s2, and this value of the case 2 and 3 are 0.58m/s2 and 0.56m/s2, respectively. The response of case 1 is about 40% higher than the other two cases.

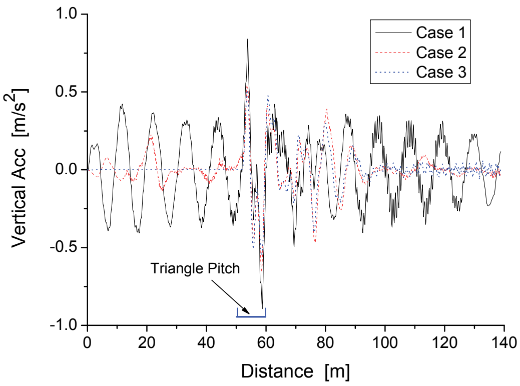


Fig. 5. Acceleration of the vehicle vibration

In case 1, the response of acceleration is very significantly due to that the vehicle's vertical motion is constrained by the additional stiffness function of the traction bar. Since subway vehicles are often in braking state, so the influence of vehicle's dynamic performance comes from the additional stiffness function of short traction bar is dramatically, especially on condition of running on curves or having vertical impact.

To solve the primary suspension spring broken phenomenon during the service, the vertical load of the spring when the subway vehicle pass the triangle pitch track is calculated and compared in this paper. Take the case 1 and case 3 for example, the braking condition and coasting condition of the existing subway vehicle is compared. Figure 6 shows the vertical load of the spring on the right primary suspension system of the first wheelset of the two cases.

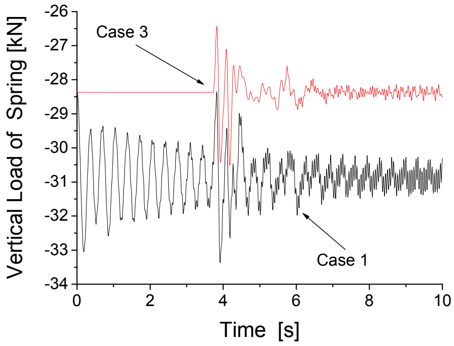


Fig. 6. Spring vertical load of the two cases

According to the figures, the vertical load of the primary spring in case 1 is big compared with that in case 3 when the subway vehicle passes the triangle pitch track, and the maximum spring load is about 34kN in case 1. Because the relative motion between the bogie and carbody was more difficult to change in the braking case than in coasting case, so the vertical load of the spring is bigger in case 1. When the subway vehicle passes the small curves, it has the same results. It indicates that the response of the subway vehicle to vertical impact is increased when the relative motion between carbody and bogie is restricted, such as in the braking case.

Vertical Frequency Response of Carbody t

The additional stiffness function of short traction bar is reflected by the increase of vertical stiffness of secondary suspension air spring. Frequency response of vertical vibration of car body show in Figure 7, which compared the normal secondary suspension state with the state consider the additional stiffness function of short traction bar. The carbody and the bogie connected rigidly through the traction bar and ignored the function of the air spring when considered the additional stiffness function of the traction bar.

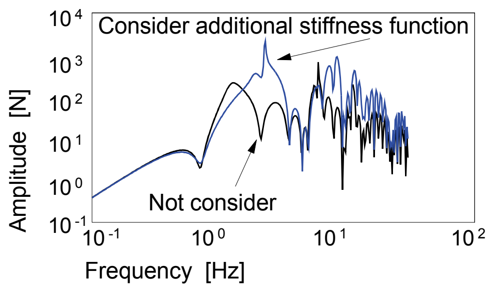


Fig. 7. The response of carbody vertical frequency

According to the figures, the responses of vertical vibration of car body increases sharply due to the additional stiffness function of short traction bar; and it is the main reason why secondary suspension lose efficient damping function and the vertical performance of car body deteriorates. The vibration of the bogie transfers to the carbody directly and lead the carbody vertical vibration with the frequency of 2Hz.

Vertical Ride Index

Figure 8 shows the vertical ride index of the subway vehicle with different speeds, in which, give the results that consider the additional stiffness function of the traction bar and that doesn't consider the additional stiffness function of the traction bar. Take the America 6 Class track irregularity spectrum as the track disturbs input, and the calculation speed is ranged from 40 to 110km/h and the interval is 10km/h.

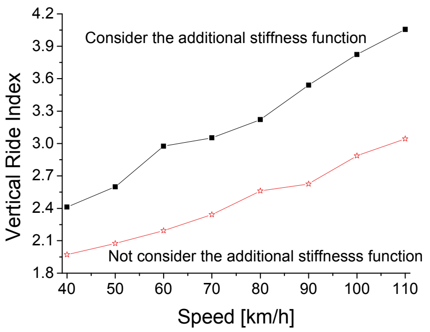
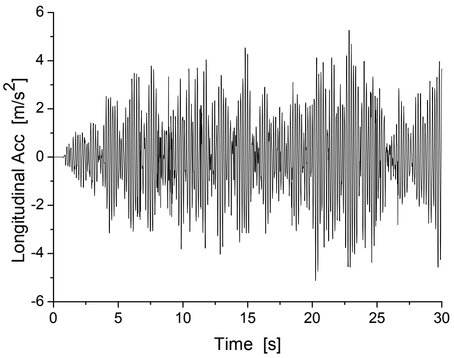
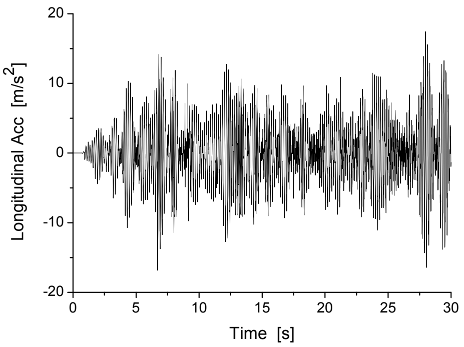


Fig. 8. Vertical ride index of the two cases

The additional stiffness function has an important influence on the vertical ride index of the vehicle. As shown in the figures, the vertical ride index of the subway vehicle when considered the additional stiffness function of the traction bar increased too much than that not considered the additional stiffness function. When considered the additional stiffness function, the vertical ride index will out of the criterion at 60km/h with the condition of new wheel match with new rail. It reflects that the additional stiffness function can increase the vertical response of the carbody to the vertical impact, and worsen the vertical ride index.



(a) Not consider the additional stiffness function



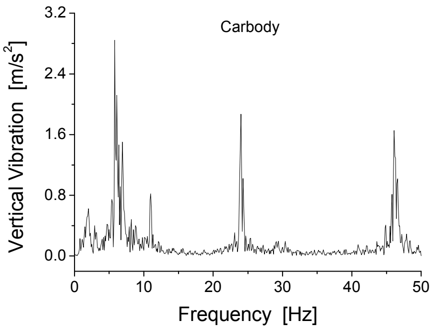
(b) Consider the additional stiffness function

Fig. 9. Wheelset longitudinal vibration accelerations

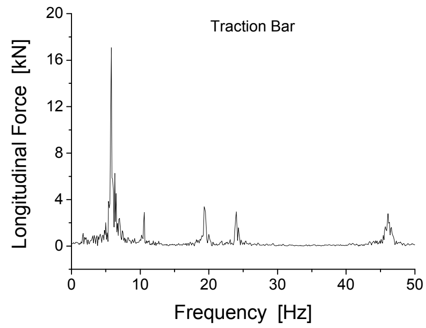
Wheelset Longitudinal Vibration Resonance

The wheelset longitudinal vibration can result in serious wear on wheel tread. According to the research of reference [19], the lighter the axle load, the easier to lead to the phenomenon of wheelset longitudinal vibration resonance. Subway vehicle has light axle load and normal longitudinal stiffness of primary suspension, if the traction bar has relatively high connection stiffness, the wheelset longitudinal vibration resonance may occur.

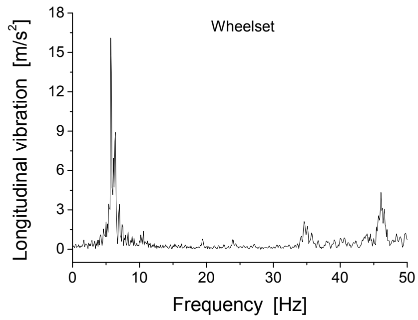
The wheelset longitudinal vibration accelerations which not consider the additional stiffness function and consider the additional stiffness function of the traction bar show in Figure 9 (a), (b), respectively. It can be seen from the figures that the wheelset longitudinal vibration acceleration is bigger when the additional stiffness function of the traction bar is considered. Therefore, the wheelset longitudinal vibration can be significantly improved by decreasing the additional stiffness function of the traction bar, and this will improve the wheel/rail contact environment as well as decrease the wheel wear.



(a) Carbody



(b) Traction bar



(c) Wheelset

Figure 10. Frequencies of carbody, traction bar and wheelset vibration

The wheelset longitudinal vibration can be transferred to carbody through the traction bar without the damping function of the secondary suspension system, and then causes the vertical vibration of carbody turn bigger. The main frequencies of carbody vertical vibration, the longitudinal force of the traction bar, and the wheelset longitudinal vibration are show in Figure 10, respectively. From these figures, it can be seen that all the vibration and forces have the same main frequency about 7.0Hz. It proved that one of the sources of the vertical vibration of carbody is the wheelset longitudinal vibration, and it caused by the additional stiffness function of the traction bar.

Improvement Methods

Decrease the stiffness or increase the length of the traction bar can avoid the form of additional stiffness function of it. For the actual traction bar structure, it can be realized by decrease the stiffness on both ends of the traction bar. The design value of the traction bar connection stiffness of the subway vehicle is 2×107N/m, decrease the stiffness to 5×106N/m, which is equal to 25% of the design value.

Figure 11 shows the vertical ride index of the subway vehicle with different speed when the traction bar stiffness is decreased to 25% of the present value. From the figures can see that all the vertical ride index of the vehicle were good even on the condition which consider the additional stiffness function. Although the ride index when considered the additional stiffness function is bigger than that not considered, the vertical dynamic performance is good during the main running speed scope from 40 to 70km/h.

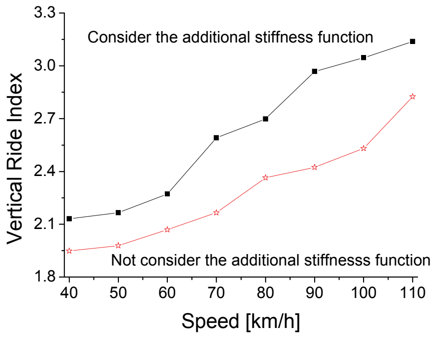


Fig. 11. Vertical ride index after improvement

Conclusions

The additional stiffness function of the traction bar maybe formed if the traction bar has short length and big stiffness. As it will cause the increase of vertical stiffness of the secondary suspension, it has an important influence on the running dynamics of subway vehicles.

When the vehicle passes curves or in braking condition, the additional stiffness function of the traction bar constrains the relative motion between carbody and bogie, which intensifies the response of carbody to the vertical impact, and results in damage of suspension components both primary and secondary suspension.

Longitudinal vibration of wheelsets caused by quasi rigid connection between carbody and bogie, it leads to further wheel wear, wheel spalling, and the appearance of wheel out-of-roundness.

The wheel wear and vertical dynamics performance worsen phenomenon of the subway vehicle can be improved by decrease the stiffness of the traction bar.

Acknowledgment

This work was supported by Project 51005190 of the National Natural Science Foundation of China, Project 20090184120006 of Ph.D. Programs New Teacher Foundation of Ministry of Education and Project 122014 of Fok Ying Tong Education Foundation.

REFERENCES

[1] F. S. Zhan, “Locomotive System Dynamics”, China Railway Publication Press: Beijing, 1990.
[2] P. Z. Carl, “The Euro sprinter family”, RTR, vol.47, No.3, pp4-11, March 1998.
[3] X. S. Jin, X. B. X, Z. F. Wen, et al. “An investigation into the effect of train curving on wear and contact stresses of wheel and rail”, Tribology International, Vol.42, Issue.3, pp475-490, March 2009.
[4] X. Sun, “the movement analyses of the traction bar system”, Diesel Locomotive, Vol.4, pp34-44, April 1978.
[5] H. P. Kaper, “Wheel corrugation on Netherlands railways (NS): origin and effects of “polygonization” in particular”, Journal of Sound and Vibration, vol.120, No.2, pp267-274, April 1988.
[6] B. Morys. “Enlargement of out-of-round wheel profiles on high speed trains”, Journal of Sound and Vibration, vol.227, No.5, pp965-978, October 1999.
[7] E. Magel, J. Kalousek, R. Caldwell, “A numerical simulation of wheel wear”, Wear, vol.258, Issue 7-8, pp1245-1254, March 2005.
[8] A. Johansson, “Out-of-round railway wheels – a study of wheel polygonalization through simulation of 3D wheel-rail interaction and wear”, Vehicle System Dynamics, vol.43, No.8, pp539-559, August 2005.
[9] A. Johansson, “Out-of-round railway wheels-assessment of wheel tread irregularities in train traffic”, Journal of Sound and Vibration, vol.293, Issue 3-5, pp795-806, 2006.
[10] R. M. Goodall, “Active railway suspensions: implementation status and technological trends”, Vehicle System Dynamics, vol.28, No. 2, pp87-118, February 1997.
[11] T. Kamada, K. Hiraizumi, M. Nagai. “Active vibration suppression of lightweight railway vehicle body by combined use of piezoelectric actuators and linear actuators”, Vehicle System Dynamics, Vol.48, Supplement, pp73-87, 2010.
[12] T. Yomioka, T. Takigami, “Reduction of bending vibration in railway vehicle carbodies using carbody-bogie dynamic interaction”, Vehicle System Dynamics, Vol. 48, Supplement, pp467-486, 2010.
[13] W. H. Ma, S. H. Luo, “Vertical vibration analysis of locomotive with radial bogies”, Chinese Journal of Mechanical Engineering, vol.43, No.4, pp65-69. April 2007.
[14] S. H. Luo, K. Q. Wang, W. H. Ma, “Abnormal vertical vibration analysis of DF8B locomotive with radial bogies”, China Railway Science, vol.27, No.1, pp83-88, January 2006.
[15] H. Y. Bao, “Research on wheels ellipse problems of subway vehicles”, Southwest jiaotong university master degree thesis, December 2007.
[16] G. Schupp, C. Weidemann, L. Mauer, “Modelling the contact between wheel and rail within multi-body system simulation”, Vehicle System Dynamics, vol.41, No.5, pp349-364, May 2004.
[17] C. Segieth, “The 12X high power locomotive”, Rail International, No.7, pp24-30, July 1996.
[18] H. J. Zhang, X. H. Chen, Y. P. Sun, et al, “The analysis of bogie platform of 200km/h high speed passenger locomotive in our country”, Journal of the China Railway Society, vol.29, No.4, pp101-106, August 2007.
[19] W. H. Ma, S. H. Luo, “Influence of Track Irregularity to Wheelset Longitudinal Vibration and the Correlation Performance”, Journal of Southwest Jiaotong University, No.14, pp238-252, March 2006.

***Authors**: prof. dr Weihua Ma, Traction Power State Key Laboratory, Southwest Jiaotong University, Chengdu, China, E-mail: maweihuab2008@gmail.com.*