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COMPARISON OF THE INFLUENCES OF THE STRUCTURAL AND SUSPENSION PARAMETERS ON VEHICLE STABILITY

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Abstract. *Vibration features of a railway vehicle with two-suspension system are closely related to vehicle structural and suspension parameters. Vehicle performance design is sensitive to vehicle mass and its distribution, as well as the wheel/rail wear. Primary longitudinal positioning stiffness, secondary anti-hunting damping and lateral damping show significant impacts on vehicle stability. The sensitivities of stability to structural and suspension parameters are analyzed and all parameters change in proportion to their design values. Sensitivity coefficient corresponding to the sprung mass is the largest and the value related to the damping of the anti-hunting damper takes second place. Influences of the mass between primary and secondary suspension, the unsprung mass and high-speed worn wheel on stability are similar. Because of the small initial equivalent conicity and the large change in conicity, the coefficient corresponding to worn profile is no morn than 0.2 although critical speed of the vehicle with the worst profiles is low. Based on effects of the single parameter on stability, influences of three parameters combination are implemented, including two types of combination. One is the combination of three key suspension parameters, the other is the combination of structural and suspension parameters. During the operation, some changes happen in the vehicle mass, damping and stiffness. Then all the three parameters vary together in the simulation. In order to maintain excellent stability, anti-hunting damping is the major adjustment factor and the compensation effect of primary positioning stiffness and lateral damping on critical speed can be available. The reductions of anti-hunting damping and sprung mass should be controlled and don't exceed 15% and 50% respectively. The safe range of each parameter is narrowed. The damping of anti-hunting damper should be strictly limited in service. Structural parameters and suspension parameters are both important to vehicle stability, and the latter should be paid more attention although they are not the most sensitive parameters.*

1 INTRODUCTION

Hunting movement, a typical self-excited oscillation, is an inherent feature of a traditional railway vehicle. Instability phenomenon of hunting should be avoided in the operation of high-speed train so that vehicle safety and ride comfort for passengers can be attained. Stability, which is one of the three vehicle dynamics performances, is a basis of vehicle design. The concept was originated in the Torricelli period of 17 century and is defined strictly by A.M. Liapunov in 1892[1]. It comprises static and dynamic stability (motion stability) and vehicle hunting stability belongs to the latter. A great deal of linear models or equivalent linearization algorithms[2-5] are set up for hunting motion, which is based on the hypothesis that wheelset displacement is small, wheel/rail interaction and suspension characteristic is linear. The eigenvalues of linear differential equations with constant coefficients are applied into the stability evaluation[6]. Nonlinear features exist in wheel/rail relationship, stiffness and damping of suspension system, which affect motion stability significantly. Numerical integration methods are used to solve the stability[8-9]. Vehicle structural and suspension parameters are the common objects of optimization design. Lightweight design, active suspension or semi-active suspension design, optimization for passive suspension are widely implemented in high-speed railway vehicle. Inertia properties of each structure, such as carbody, bogie or wheelset and stiffness or damping range of primary and secondary suspension systems are determined by parametric study and sensitivity research[10-17].

2 PARAMETRIC SENSITIVITY ANALYSES

Vehicle performance is sensitive to vehicle mass and its distribution, as well as the wheel/rail wear. In earlier studies of vehicle stability, researchers used to calculate the equivalent stiffness (shear stiffness and bending stiffness[18]) for vehicle suspension system and then worked out the critical speed V_{cr}, which is an important index of hunting stability. V_{cr} is inversely proportional to square root of unsprung mass. However, mass of bogie frame is used to be overlooked[19]. J.K. Hedrick and his research group built the vehicle model with equivalent shear and bending stiffness and took mass of bogie frame into account[20]. Then V_{cr} was derived as follows:

$$V_{cr} = \left[\left(\frac{A}{M_w} - B \right) \frac{M_w}{M_w + M_f / 2} \right]^{\frac{1}{2}} \tag{1}$$

In which, A and B are related to some structural parameters, such as shear stiffness, bending stiffness, wheelbase, wheel radius, equivalent conicity and so on. They are irrelevant to vehicle mass. Formula (1) shows $V_{cr} \propto 1/M_w$ and $V_{cr} \propto 1/M_f$, and there is a square root relationship. In addition, V_{cr} is related to mass ratio M_f: M_w.

At the present, a vehicle model for a high-speed train in China is set up without simplified equivalent shear and bending stiffness by multibody dynamics software SIMPACK, where the Kalker's linear rolling contact theory is applied in. China high-speed wheel profile LMA and rail profile CN-60 are introduced and the initial equivalent conicity is the lowest, 0.0385. There are 50 degrees of freedom. Variations on the following parameters of the vehicle are performed:

- Carbody mass or sprung mass M_c, and the corresponding moments of inertia;
- Bogie frame mass or the mass between primary and secondary suspension M_f, and the corresponding moments of inertia;
- Wheelset mass or unsuprung mass M_w, and the corresponding moments of inertia;
- Primary longitudinal positioning stiffness K_{px} ;

- Secondary lateral damping C_{sy} ;
- Secondary damping of antihunting damper C_{sx};
- Equivalent conicity of actual worn wheel and new rail λ_e;

Vehicle parameters mentioned above change in proportion to the initial design values, except the last one λ_e. Seven parameters are modified one at a time, and eleven values are assigned to the first six parameters. The conicity is determined by the actual wheel profiles and the maximum percentage of increment variation should be larger than 200%.

Critical speed is a function of percentage of vehicle parameter's variation[16] as shown in Figure 1. Each parameter sensitivity for V_{cr} can be seen clearly. The critical speed for the initial state of the vehicle, where the parameter variation equals to 0%, is about 530 km/h and it is the base point for all the following proportion calculation. Decreasing the primary longitudinal suspension stiffness K_{px} and secondary lateral damping C_{sy} (+50%→-50%) is favourable for stability if the other parameters do not change. The effects of M_f and M_w is similar to that of K_{px}. The three curves are so close to each other. Increasing C_{sx} or M_c (-50%→+50%) is good for stability and the variations of critical speed (661km/h) for C_{sx} is the largest, as shown in Table 1. Range of V_{cr} changed by M_c or M_w is larger than that for K_{px} (449km/h). Value of critical speed depends strongly on the six parameters.

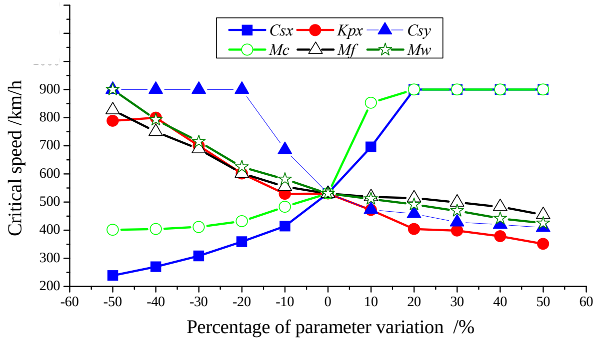


Figure 1: Relationship between critical speed and parameter variation

C_{sx}	661 km/h
K_{px}	*449* km/h
C_{sy}	*491* km/h
M_c	**499** km/h
M_f	372 km/h
M_w	**475** km/h

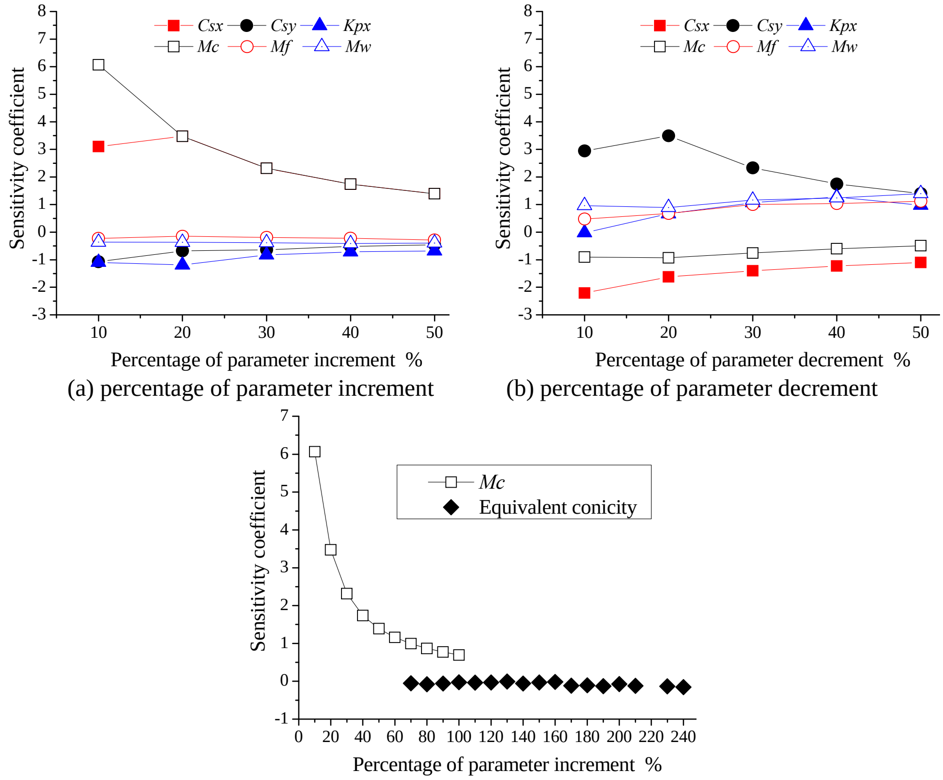
Table 1. Range analysis of V_{cr}

In order to describe further the sensitivity of parameters, a sensitivity coefficient D is introduced as follows:

$$D = \frac{\Delta y}{y} \Big/ \frac{\Delta x}{x} \tag{2}$$

Relative sensitivity level is judged by sensitivity coefficient. There is no unit and it is irrelevant to parameters or performance characteristic. It can be adapted to analyze the sensitivity of any parameters for different performances.

The comparison of sensitivity coefficient is made in Fig.2. There are some differences between the increasing and decreasing situation. When the increase ratio of parameter is less than 15%, the coefficient for sprung mass M_c is the largest and it is equal to 6, as shown in Fig2(a). The second largest value is for anti-hunting damping C_{sx}, and then the third is the absolute value for primary longitudinal stiffness K_{px}. The coefficients for the parameters M_c and C_{sx} decrease with the percentage increment increasing. When the parameters decrease, the absolute values of corresponding coefficients vary within 4 and the sensitivity for secondary lateral damping C_{sy} is the highest, see Fig2(b). However, for the worn profile, due to the small the initial equivalent conicity and large change ratio as the denominator, the coefficient is less than 0.5. It is similar with the results for M_f and M_w. Therefore, the initial design status of the vehicle is sensitive to the increments of carbody mass and anti-hunting damping and the decrement of lateral damping.



(a) percentage of parameter increment (b) percentage of parameter decrement

(c) comparison between M_c and conicity

Figure 2: Parameter sensitivity coefficient

3 EFFECTS OF THREE PARAMETERS ON VEHICLE STABILITY

3.1 Combination of three suspension parameters

Based on effects of the single parameter on stability, three key suspension parameters can be selected, which are anti-hunting damping, lateral damping and longitudinal positioning stiffness. This section tries to analyze the influence of three parameters simultaneous change. Considering the increment percentage from 10%~40%, the results are shown in Fig 3 and Fig 4. Values of critical speed under all the parameter combinations are greater than 350km/h and percentage of speed varies -25%~70% , which is relative to the initial status. Influence of single parameter is also shown in the results, which is described by the line with symbols in Fig 4. Each bar with shadow in Area I in Fig 4 shows the percentage of critical speed affected by a combination of K_{px} and C_{sy} for each C_{sx} increment. Likewise, Area II and Area III can be explained. Critical speed increases by 30% affected by a single parameter C_{sx} variation, where the increment ratio is only 10%, however, the percentage of speed varies from -25% to 10% when the other two parameters change together. In other words, the worst attenuation effect of increases of K_{px} and C_{sy} can be approach 55% when C_{sx} increases by 10%. Height of bars in the graph represents the adjustment ability of parameter combination to stability. As a whole, the average height of bars associated with C_{sx} is higher, such as the values in Area II and Area III. Therefore, the influence of decrement of C_{sx} on stability is introduced in the critical speed distribution, see Fig 5. Vehicle safety domain, where the critical speed is larger than 350km/h, is shrinking when C_{sx} decreases from 10% to 40%. When C_{sx} decreases by 20% and above, critical speed is less than 350km/h whatever the parameter combination is, and the vehicle is in danger. To ensure enough vehicle safety domain, the control of anti-hunting damping is the key step and the compensation effect of primary positioning stiffness and lateral damping on critical speed can be available.

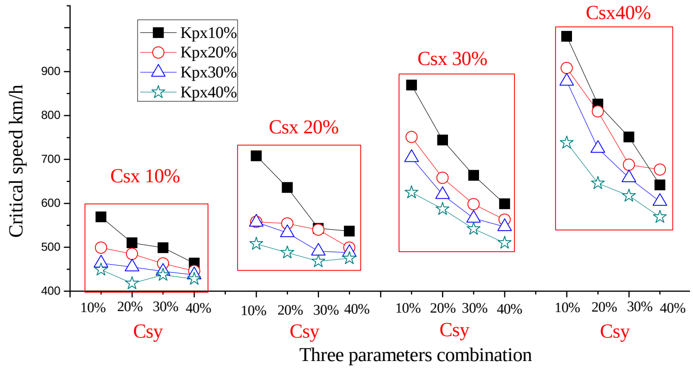


Figure 3: Influence of three parameters on critical speed

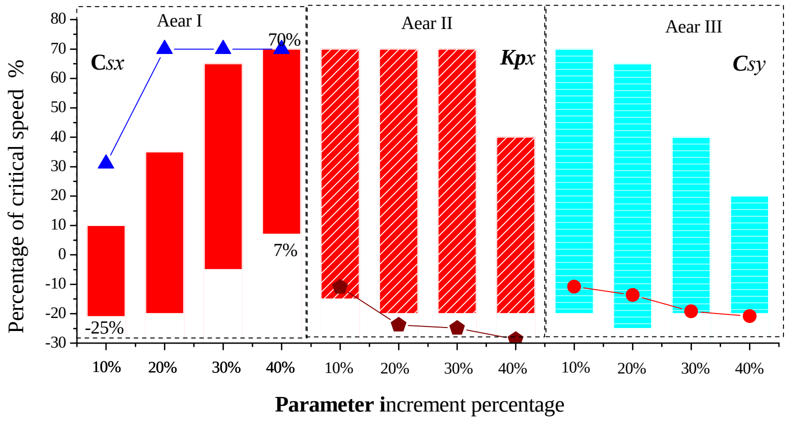


Figure 4: Comparison between the effect of single parameter and that of three suspension parameters

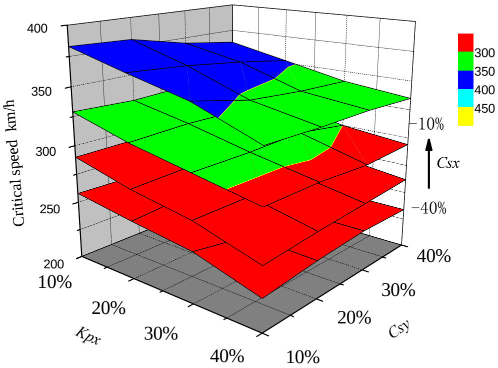


Figure 5: Critical speed distribution based on three suspension parameters

3.2 Combination of structure and suspension parameters

During the operation, some changes happen in the vehicle mass, damping and stiffness. Three key structural and suspension parameters are chosen in this section, which are sprung mass, anti-hunting damping and longitudinal positioning stiffness. Percentage of critical speed affected by the combination of M_c, C_{sx} and K_{px}, as shown in Fig 6. When C_{sx} decreases by 50% in Area I, critical speed declines by 10% ~ 56% under the combination of M_c and K_{px}. No matter what K_{px} is in Area II, changes of the other two parameters lead to a wide range of critical speed percentage variation, -50% ~ +80%. The average height of bars in Area II is the highest, which is related to the changes of M_c and C_{sx}.

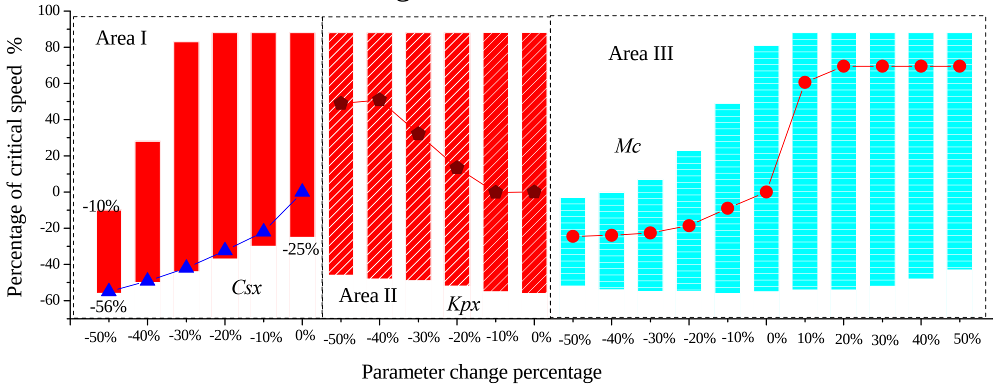
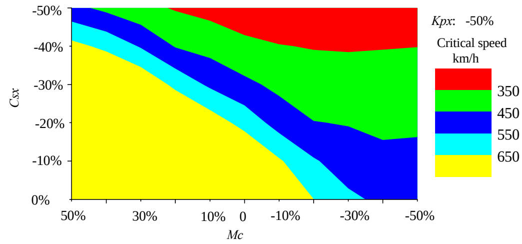
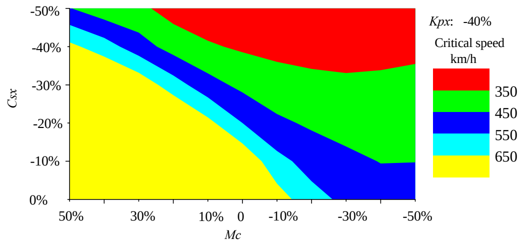


Figure 6: Effect of structural and suspension parameters on critical speed

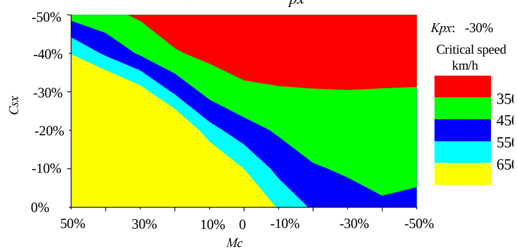
In order to show influences of combinations intuitively, critical speed distribution for each longitudinal stiffness is plotted in Fig 7. There is a wide distribution, which means both the results of 350km/h below and 650km/h above are calculated. With K_{px} increasing, the dangerous area, where the critical speed is less than 350 km/h, is getting bigger gradually and the area ratio of the distribution changes from 1/10 to nearly 1/2. When K_{px} equals to the design value in Fig 7(f), vehicle can be safe if C_{sx} and M_c decrement percentages don’t exceed by 15% and 50% respectively. In order to maintain excellent stability, safe range of each parameter is narrowed. The damping of anti-hunting damper should be strictly limited in service.



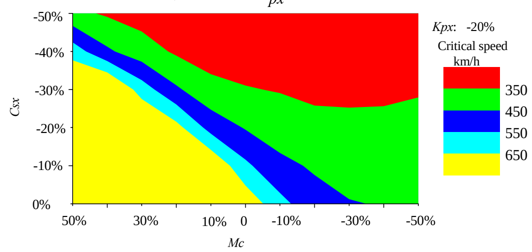
a） -50% K_{px}



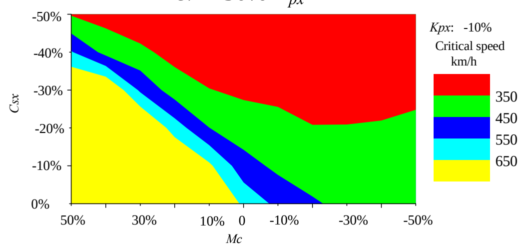
b）-40% K_{px}



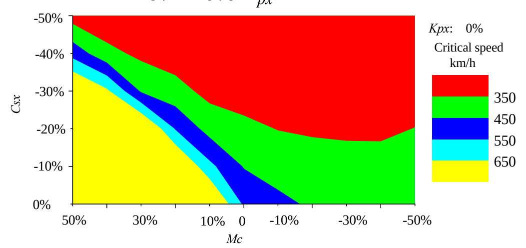
c） -30% K_{px}



d）-20% K_{px}



e） -10% K_{px}



f）0% K_{px}

Figure 7: Critical speed distribution based on M_c, C_{sx} and K_{px}

4 CONCLUSION

Structural parameters and suspension parameters are both important to vehicle stability, and the latter should be paid more attention although they are not the most sensitive parameters. The sensitivity coefficient of sprung mass is large and can not be neglected in stability research.

There are some differences between the effect of single parameter and that of multi-parameter combination. Critical speed distribution is a good way to represent the influence of parameters combination. In order to maintain excellent stability, the reductions of anti-hunting damping and sprung mass should be controlled and don’t exceed by 15% and 50% respectively.

Because of the small sensitivity coefficient for worn wheel profiles, the conicity is not be regarded as the key parameter. However, the result can be only concluded that stability is insensitive to conicity percentage variation, not concity. In fact the conicity for worn wheel profile increase a lot in a short service time and affects the critical speed significantly. The changes for suspension parameters takes a long time and the change rates are almost controlled in 30%. Therefore, the relationship between service time and change rate of structural and suspension parameters should be considered in future research.

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