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Influence of Semi-active Suspension on Running Safety of Vehicles

Hong-You Liu† and Da-Lian Yu*

Abstract

Railway vehicles equipped with semi-active suspension system can improve the ride quality of car bodies. Semi-active suspension system is usually applied onto high speed train, and therefore higher running safety requirement is desirable. The influence of semi-active suspension system on safety of vehicles running on straight line and curve line is studied, and the influences of sky hook damping coefficient and system time-delay on operational safety of cars fitted with semi-active suspension system is analyzed. The results show that in vehicles equipped with semi-active suspension system, while the vibration of car body is decreased, the running safety of cars is not affected to any significant degree. As a result, the ride quality is much improved with negligible deterioration of the running safety of cars.

Keywords **:** *Semi-active suspension, On/off damping control, Continuous adjustable damping control, Sky hook, Running safety*

1. Introduction

Application of active and semi-active control technology for improving the ride quality of cars has been one of the development trends of high speed vehicles system design [1-7]. In most cases, the active control uses lateral velocity of car body as feedback control variable. The vibration performance of cars in low frequency range can be improved without lowering the high frequency vibration performance. Application of semi-active damper with low energy consumption can produce damping force between car body and bogie, the magnitude of force is close to active control, which can reduce the vibration of car body. The multi-body dynamics software SIMPACK is used to establish a test car virtual prototype model with SW-200 bogies, the influence of secondary lateral semi-active suspension based on sky hook control on the running safety of the test car is researched, and the influences of sky hook damping coefficient and system time-delay on running safety of the test car equipped with semi-active suspension system is analyzed.

† Corresponding author: Semi-active Suspension Department, Qingdao Sifang Rolling Stock Research Institute Co., Ltd, China.
E-mail: LHYLL@126.com
* Technique Center, CSR Sifang Locomotive and Rolling Stock Co.,Ltd, China.

2. Simulation Model

2.1 Vehicle System Model

The dynamics simulation model of the test car is set up with SIMPACK, the degrees of freedom(D.O.F) and generalized coordinates is shown in Table 1. In all, 56 D.O.Fs are considered in the model, for which 8 are non-independent, the simulation model is shown as Fig 1. In the model, the nonlinear factors of suspension are well considered. The damping force produced by secondary lateral semi-active suspension dampers is built in SIMPACK electromechanical control module. it is easily adjusted according to the variable control schemes.

2.2 Damping Force of Secondary Lateral Damper

Under passive, on/off damping control semi-active and continuous adjustable damping control semi-active conditions, the law of damping force of secondary lateral damper (hereinafter refer to damper) is as follows [8]:

In case of passive condition:

$$F_r = -C_r(v_1 - v_2) \tag{1}$$

In case of on/off damping control semi-active condition:

$$F_r = \begin{cases} -C_r(v_1 - v_2) & v_1(v_1 - v_2) > 0 \\ 0 & v_1(v_1 - v_2) \le 0 \end{cases} \tag{2}$$

Table 1 Degrees of Freedom for the Test Car Model (*Non-independent Freedom of Motion)

Rigid body	Longitudinal displacement	Lateral displacement	Vertical dispalcement	Roll	Pitch	Yaw	Remarks
Carbody	X_C	Y_C	Z_C	ϕ_C	θ_C	ψ_C	
Bolster			$Z_{b\,k}$	$\theta_{b\,k}$		$\psi_{b\,k}$	$k=1\sim2$
Bogie frame	$X_{f\,i}$	$Y_{f\,i}$	$Z_{f\,i}$	$\phi_{f\,i}$	$\theta_{f\,i}$	$\psi_{f\,i}$	$i=1\sim2$
Wheelset	$X_{w\,i}$	$Y_{w\,j}$	$Z_{w\,j\,*}$	$\phi_{w\,j}$	$\theta_{w\,j}$	$\psi_{w\,j}$	$j=1\sim4$
Rotating arm					$\theta_{a\,m}$		$m=1\sim8$

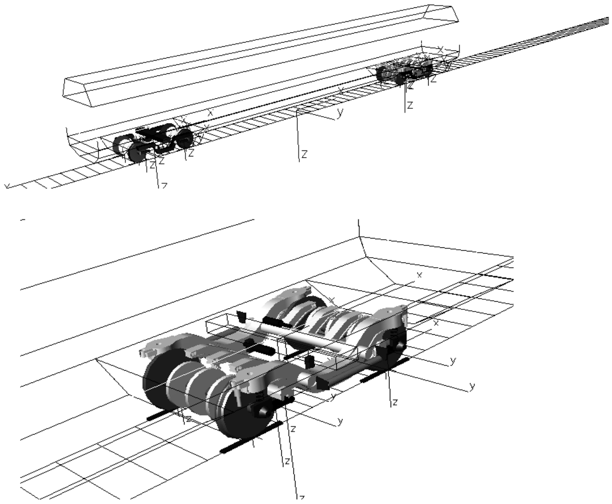


Fig. 1 Simulation model of the test car

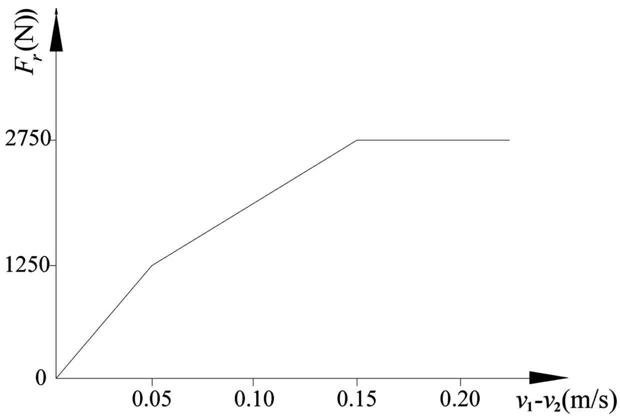


Fig. 2 Damping characteristics of passive damper

In case of continuous adjustable damping control semi-active condition

$$F_r = \begin{cases} -C_{sky}v_1 & v_1(v_1 - v_2) > 0 \\ 0 & v_1(v_1 - v_2) \le 0 \end{cases} \tag{3}$$

where, C_r —Damping coefficient of passive damper, v_1 —Lateral velocity of car body, v_2 —Lateral velocity of bogie frame, C_{sky} ——Sky hook damping coefficient. The stiffness of of each rubber nod on both ends of the damper is considered to be 20 MN/m, and the relationship between damping force and piston velocity under passive condition is as shown in Fig. 2.

3. Influence of Semi-active Suspension System on Vehicle's Running Safety

Wheel/rail lateral force(Q), wheelset lateral force(H), derailment coefficient(Q/P) and wheel load reduction rate($\Delta P/P$) are used to evaluate the running safety of the car. German high speed track spectrum is used as rail irregularities.

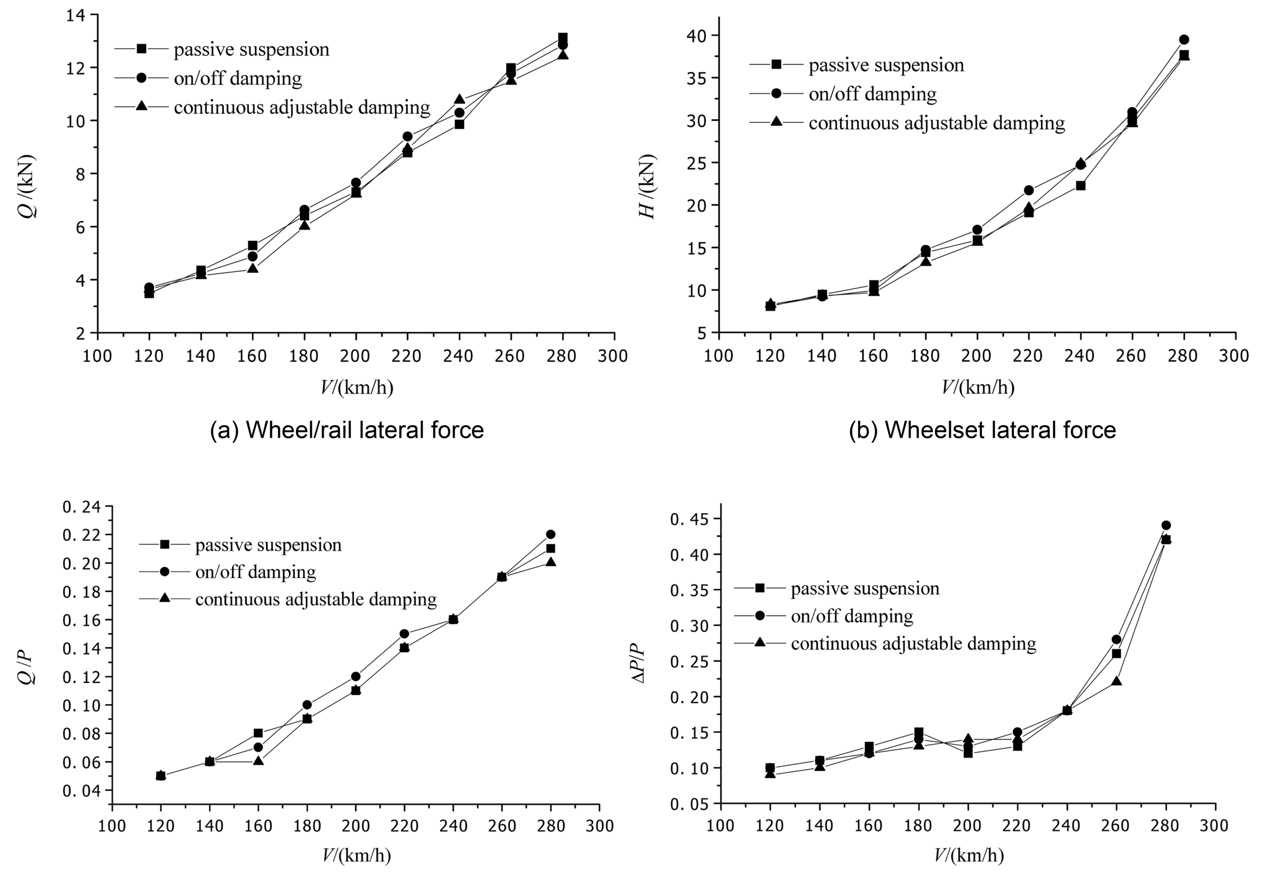
It is generally considered that running safety of vehicles equipped with semi-active suspension would not be worsening as well as improving the riding comfort of car bodies. Even in some cases, the wheel/rail lateral force may be decreased [9]. Alternatively, vibration performance of the bogie can be worsened due to the reason that semi-active damper cuts off the useful force to damp vibration of bogies [10]. Therefore, it is necessary to analyze the running safety of the car equipped with semi-active suspension system.

3.1 Running Safety on Lines

The results of Q、H、Q/P and $\Delta P/P$ for the test car equipped with different suspension system running at variable speed V is as shown in Fig. 3.

It is known from Fig. 3, the semi-active suspension system will cause very less effect on running safety of the test car, and safety index values are all nearly similar to those of passive suspension system.

While $V = 200$ km/h, the RMS value of lateral wheel/rail force for leading wheelset is 1.32 kN under the passive condition. It is 1.10 kN under on/off damping control semi-active state. It is 1.03 kN under continuous adjustable damping control semi-active state. The RMS value of leading wheelset lateral force is 2.44 kN under passive condition. It is 2.05 kN under on/off damping control



(a) Wheel/rail lateral force

(b) Wheelset lateral force

(c) Derailment coefficient

(d) Wheel load reduction rate

Fig. 3 Safety index of the test car running on straight line

semi-active state. It is 1.82 kN under continuous adjustable damping control semi-active state. It is obvious that maximum values of wheel/rail lateral force for the car equipped with semi-active suspension are similar to that of the car with passive suspension, however, the RMS value is smaller, indicating that the car equipped with semi-active suspension system decreased the lateral wheel/rail force when the car running at some speed.

3.2 Running Safety on Curves

The calculation cases for the test car negotiating the curves are shown as Table 2.

According to the calculation results shown in Table 3, the conclusion is the same as that on lines, no significant change on the negotiating performance for the car equipped with the secondary lateral semi-active suspension system, particularly, continuous adjustable damping control semi-active suspension system can also more or less reduce the wheel/rail lateral force and derailment coefficient, so as to improve the curving performance of the

Table 2. Calculation Cases on Curves

S. No.	Curve radius/m	Cant/mm	Curving speed/(km/h)
1	300	100	40
2	300	100	50
3	300	100	70
4	600	80	50
5	600	80	65
6	600	80	80
7	800	60	50
8	800	60	65
9	800	60	100
10	1200	50	60
11	1200	50	70
12	1200	50	120
13	2000	100	60
14	2000	100	80
15	2000	100	150

Table 3 Safety Indexes for Cars Negotiating Curves

S. No.	Passive				On/Off damping control semi-active				Continuous adjustable damping control semi-active			
	Q/kN	H/kN	Q/P	$\Delta P/P$	Q/kN	H/kN	Q/P	$\Delta P/P$	Q/kN	H/kN	Q/P	$\Delta P/P$
1	33.94	14.35	0.54	0.18	33.46	14.57	0.51	0.19	32.81	14.95	0.50	0.19
2	35.73	13.27	0.51	0.25	35.49	12.20	0.51	0.26	35.03	12.73	0.50	0.26
3	38.71	23.21	0.39	0.50	39.21	23.07	0.40	0.49	38.31	22.29	0.40	0.49
4	26.75	14.81	0.40	0.14	27.24	14.79	0.42	0.14	26.41	14.43	0.41	0.17
5	27.14	13.05	0.39	0.23	28.06	13.23	0.41	0.23	27.90	13.06	0.40	0.23
6	29.78	16.47	0.34	0.33	29.93	16.36	0.35	0.31	29.27	15.84	0.34	0.32
7	23.56	14.71	0.34	0.10	23.97	14.88	0.34	0.10	22.79	14.04	0.32	0.14
8	23.44	12.83	0.32	0.18	23.82	12.85	0.33	0.18	23.18	12.68	0.32	0.18
9	29.39	22.66	0.30	0.42	29.63	22.41	0.30	0.40	27.87	23.01	0.29	0.38
10	21.07	13.09	0.29	0.11	20.32	13.34	0.30	0.12	19.22	12.80	0.28	0.12
11	19.32	12.34	0.26	0.15	20.44	12.68	0.27	0.15	18.29	11.79	0.25	0.15
12	35.65	25.31	0.35	0.48	33.30	25.02	0.34	0.44	31.19	23.28	0.31	0.44
13	24.74	22.92	0.22	0.15	23.45	19.51	0.47	0.15	18.93	19.17	0.42	0.17
14	22.17	24.39	0.28	0.18	22.07	20.00	0.49	0.19	21.68	19.79	0.49	0.45
15	32.59	23.06	0.40	0.42	32.79	25.08	0.42	0.45	31.76	20.61	0.39	0.41

car. The reason is that the negotiating performances of cars mainly depend on the primary suspension system of the bogie. The damping effect of semi-active suspension on the lateral random vibration for the cars is obvious. Meanwhile, the secondary lateral semi-active suspension system nearly has no effect on the vertical vibration of the cars.

4. Influence of Semi-active Suspension Parameters on Vehicle's Running Safety

4.1 Influence of C_{sky} on Vehicle's Running Safety

In case of no change to the other parameters of the test car, the dynamics performance of the test car is calculated for the car running at 200 km/h on German high speed track spectrum lines, and C_{sky} varied from 10 kN·s/m to 220 kN·s/m.

It is shown from the calculation results that the bigger for C_{sky}, the smaller for index of lateral riding comfort of the car body, however, when C_{sky} is bigger than 150 kN·s/m, the RMS value of lateral ridding comfort and lateral acceleration of the car body decrease slightly, even fluctuate, meanwhile, the lateral acceleration of car body appears more peak, high frequency vibration will be dramatically increased, which will weaken the effect of the semi-active suspension system, it also brings more difficulty [8,9] for the design of control system.

C_{sky} gives very little influence on Q 、H 、Q/P and $\Delta P/P$. When C_{sky} increases from 25 kN·s/m to150kN·s/m, the lateral wheel/rail force only increases approximately 220 N, still less than the level under passive suspension.

According to the above analysis, C_{sky} is selected to be 150 kN·s/m.

When the damping coefficient of the on/off semi-active suspension is selected as the same value of the passive damper, magnitude of damping force is quite close to each other. Once the semi-active suspension system failed, it will be automatically changed to the passive state, in view of that, the damping characteristic of on/off damping control semi-active suspension also can be selected as the same of the passive ones.

4.2 Influence of System Time Delay on Vehicle's Running Safety

In practical application, there are many time delay factors for the semi-active suspension system. and the time delay will cause significant effects for semi-active suspension system, therefore, it is necessary to study the influence of time delay on dynamics of the semi-active suspension system.

During the simulation, the time delay

$$G(s) = e^{-t_d s} \tag{4}$$

is added into control system in the prototype model, where t_d is system time delay, by approaching second order Pade approximation method, $G(s)$ is converted to:

Table 4 Influence of Time Delay on Vehicle's Running Safety on Lines

System time delay/ms	*Q*/kN	*H*/kN	*Q*/*P*
10	7.22	16.5	0.11
20	7.42	16.85	0.124
30	7.45	17.81	0.126
40	7.5	17.9	0.128
60	7.56	17.92	0.136
80	7.97	18.26	0.136
100	9.53	19.54	0.139

$$G(s) = \frac{\frac{12}{t_d^2} - \frac{6}{t_d}s + s^2}{\frac{12}{t_d^2} + \frac{6}{t_d}s + s^2} \quad (5)$$

Suppose the test car runs at the speed of 200 km/h on lines with German high speed track spectrum, when the time delay for the continuous adjustable damping control semi-active suspension system(C_{sky}=150 kN·s/m) varies from 10 ms to 100 ms, the results for lateral vibrations of the car and running safety index are shown in Table 4.

As shown in Table 4, with the increase of time delay, *Q* and *H* increase respectively, *Q*/*P* increases slightly, however, during the design of cars, safety is usually taken into the consideration in case of fail of lateral dampers, so the time delay can not endanger the running safety of the car. The variation of wheel load reduction rate and wheel/rail vertical force is very small, which is not included in Table 4.

In view of the damping effect, t_d is better to be controlled within 60 ms.

5. Conclusion

(1) The semi-active suspension system can reduce the vibration of the car body. Simultaneously, it will cause slight modification on the running safety index of cars either running on straight lines or curves. The vibration level of bogie and wheelset can be decreased by applying for the semi-active suspension system. Generally speaking, whether the cars run on straight lines or curves, the secondary semi-active suspension system exerts slight influence on the dynamic performance of both bogies and wheelsets. Hence it will not endanger the running safety of the car.

(2) The sky hook damping of continuous adjustable damping control semi-active suspension system generates a significant effect on ride comfort of car bodies, but has little effect on running safety for the cars.

(3) The system time delay has significant effect on ride comfort of the car body for the car equipped with continuous adjustable damping control semi-active suspension system, but shows little effect on running safety of the cars equipped with on/off damping control semi-active suspension system. When system time-delay is controlled to be within 60 ms, the system time-delay will cause limited effect on running safety of cars equipped with semi-active suspension system.

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