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# Strategy and Modelling of Semi-Active Suspension Hybrid Control for High-Speed Railway Vehicles: Using CRH2C Electric Multiple Units as an Example

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**Abstract:** The increasing operating speed of high-speed electric multiple units (EMUs) intensifies the lateral vibration of the vehicle and degrades the riding comfort. Taking the CRH2C EMU as the research object, this paper establishes a vehicle dynamics model in VI-Rail and conducts a co-simulation with MATLAB/Simulink. A semi-active suspension hybrid control strategy based on the Skyhook and Groundhook strategies is proposed, in which the weighting factor $\alpha$ regulates the relative contribution of the two strategies. For a train running at 70 m/s (252 km/h) on a track characterised by the standard German linear low irregularity spectrum, the peak value and the root mean square (RMS) value of the lateral acceleration of the car body are used as evaluation indices to compare the hybrid control with the passive control. The results show that when $\alpha$ falls within the range of 0.9-1.0, the hybrid control suppresses the lateral vibration more effectively than the passive control, reducing the RMS values of the lateral acceleration of the car body by up to approximately 5.1%; when $\alpha$ approaches 0, that is, when the control degenerates into the pure Groundhook strategy, the performance is inferior to that of the passive control. The proposed strategy improves the riding comfort of high-speed EMUs without modifying the vehicle structure, and a weighting factor in the range of 0.9-1.0 is recommended for engineering application.

**Key words:** high-speed railway; semi-active suspension; hybrid control strategy; VI-Rail; MATLAB/Simulink

**CLC number:** U260.11

## 0 Introduction

Among various transportation systems, the railway is widely recognised as an efficient, safe, and sustainable mode of transportation. Along with the increasing speed, the vibration of vehicles has been significantly enhanced, which brings new challenges to researchers with higher requirements of riding comfort and running safety. The passive suspension system has its inherent limitations when adapting to varying track irregularities and running speeds[1-2]. Though the active suspension system avoids these limitations, its reliability, high power, hardware complexity, and maintenance issues restrict its further development[3-4]. The semi-active suspension system seeks to amalgamate the benefits of both passive and active suspensions by employing variable dampers capable of real-time adjustment of damping characteristics. Karnopp[5] revealed that semi-active suspension

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could reduce lateral vibration as well as active suspension. Additionally, the semi-active suspension provides a shorter response time when compared with passive suspension[6-7]. Furthermore, the semi-active control systems provide better stability via adjustable damping than active suspensions[8].

Guo[9] introduced a semi-active suspension by using a hybrid control strategy in 2013. By establishing a vehicle dynamic model with two degrees of freedom, this research proved its effectiveness in suppressing the lateral vibration. In 2020, Leblebici and Türkay[10] applied the hybrid control. With the aid of advanced optimisation algorithms based on gradient and LMI techniques to synthesise the bi-static damping coefficients, a multi-objective optimisation problem was solved. In 2021, Díaz-Choque *et al*[11] introduced a novel methodology based on optimisation techniques to systematically design controllers in semi-active suspension systems for the hybrid control strategy. The authors implemented a hybrid artificial bee colony and genetic algorithm approach to concurrently optimise the Hybrid control policies. However, these studies only conduct simulations for part of the situations, which causes difficulties in deriving a comprehensive and accurate comparison and assessment of the comfort aspect of multiple-unit train operations at different running conditions.

To address these limitations, this paper proposes a hybrid control strategy, combining the Skyhook and Groundhook control strategies[12-13], to achieve a more balanced solution for lateral vibration of high-speed vehicles at a speed of 70 m/s under multiple track conditions. A high-speed rail model is built under the VI-Rail environment and simulated under the MATLAB/Simulink environment to verify the effectiveness of the proposed strategy.

# 1 The Hybrid Control Strategy and Combined Simulation

## 1.1 The Theory of the Hybrid Control Strategy

Semi-active suspension systems are the execution units (EU) of mitigating vehicle lateral vibrations. Control strategies can be broadly categorised into two classes according to the controlled object: one suppresses the lateral vibration of the sprung mass, and the other that of the unsprung mass[3,9,14-15]. The first category can directly restrict the vibration of the car body of high-speed railway, improving the ride comfort of the vehicle[5,16]. Skyhook control is one of the most exemplary control strategies within this particular category. The second category improves running safety by suppressing the lateral vibration of bogies and wheelsets, like Groundhook control. Both control strategies ignore indicators that are critical for high-speed railways. Skyhook control ignores the running safety issues whereas Groundhook control considers only running safety. By introducing the weighting factor $\alpha$, the characteristics of Skyhook and Groundhook control strategies are integrated into the hybrid control strategy. The expression of the hybrid control strategy in on-off mode is Equation (1).

$$
\begin{aligned}
F_{\mathrm{sky}} &= \begin{cases} \alpha C_{\max}\left(\dot{Z}_b - \dot{Z}_w\right), & \left(\dot{Z}_b - \dot{Z}_w\right)\dot{Z}_b \geqslant 0 \\ \alpha C_{\min}\left(\dot{Z}_b - \dot{Z}_w\right), & \left(\dot{Z}_b - \dot{Z}_w\right)\dot{Z}_b < 0 \end{cases} \\
F_{\mathrm{gnd}} &= \begin{cases} -(1-\alpha) C_{\max}\left(\dot{Z}_b - \dot{Z}_w\right), & \left(\dot{Z}_b - \dot{Z}_w\right)\dot{Z}_w \leqslant 0 \\ -(1-\alpha) C_{\min}\left(\dot{Z}_b - \dot{Z}_w\right), & \left(\dot{Z}_b - \dot{Z}_w\right)\dot{Z}_w > 0 \end{cases} \\
F &= F_{\mathrm{sky}} - F_{\mathrm{gnd}} \\
C_{\mathrm{hyd}} &= \frac{F}{\left(\dot{Z}_b - \dot{Z}_w\right)} \\
\alpha &\in [0,\ 1]
\end{aligned}
\tag{1}
$$

where $Z_w$ represents the difference in the lateral position (displacement) of the unsprung mass. $Z_b$ represents the difference in the lateral position (displacement) of the sprung mass. Their differential coefficients represent the lateral velocity of the sprung or unsprung mass. $C$ is the core of the algorithm, which represents the damping coefficient of lateral suspensions. The ideal damping coefficient is denoted as $C_s$. The maximum and minimum of the damping coefficient that can be adjusted would be $C_{\max}$ and $C_{\min}$, respectively. $C_{\mathrm{hyd}}$ represents the virtual damping coefficient of the vehicle system. $F_{\mathrm{sky}}$ and $F_{\mathrm{gnd}}$ respectively represent the damping force of Skyhook control and the Groundhook control.

As $\alpha$ transitions from 0 to 1, priority shifts gradually from full Groundhook authority to complete Skyhook authority over the semi-active damping force command. This produces a spectrum of hybrid controllers spanning the two extremes. The unified algorithm provides a spectrum of controllers between Skyhook ($\alpha$=1) and Groundhook ($\alpha$=0) configurations. Intermediate $\alpha$ selections enable customisable balancing of ride comfort

and handling metrics[11,14,17]. This approach seamlessly integrates the two damping modalities, simultaneously enabling superior dynamic performance for both the sprung and unsprung mass.

### 1.2 Modelling Under the VI-Rail Environment

In China, the highest design speed of electric multiple units (EMUs) is 300 km/h. The operating speed of the EMUs is around 275 km/h. Therefore, the tested train was a conventional CRH2C EMU, moving at a commercial operating speed of 70 m/s, or roughly 252 km/h. Yan *et al*[17] and Zhai *et al*[18] revealed the major parameters of CRH2C. A VI-Rail model was used to examine and analyse the lateral vibration of the train under track irregularities. It provides an extensive modelling platform for analysing the railway vehicle system's overall performance.

In this study, the car body, bogie frames, and wheelsets exhibit much greater rigidity in comparison to the bogie suspensions (much larger stiffness). As a result, in the VI-Rail model, they are considered rigid bodies. During the following co-simulation, these parts of the carriage will not deform.

The track situation includes the track parameters and the track irregularities. The track parameters include the geometric properties of the track centreline. To reproduce realistic running conditions in the subsequent co-simulation, the track centreline includes both straight and curved sections. The track curves in the simulation include both the straight track centreline and the curvature track centreline.

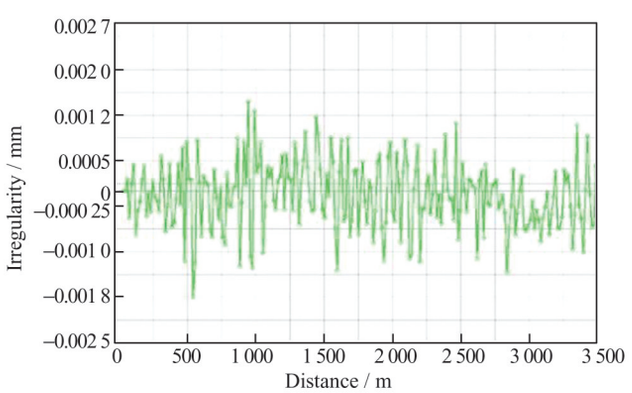



**Fig. 1 The lateral left track irregularities**

During the investigation of the vibration performance of high-speed trains, it is imperative to comprehensively consider the influences of both short-wave and long-wave track irregularities. Advances in rail manufacturing and laying technologies have significantly mitigated the impact of short-wave irregularities[12]. Nevertheless, as high-speed train velocities continue to increase, the persistence of long-wave disturbances emerges as a critical factor influencing vibration performance. These disturbances possess the capacity to elicit significant vibrations, thereby compromising both the comfort and safety of the train. The Power Spectral Density (PSD) is typically characterised by a Stationary Stochastic Process, which describes these irregularities. In this study, consideration is limited to the *Y* direction irregularities due to a specific focus on lateral vibration. The lateral irregularities of the left and right rails are depicted in Fig. 1 and Fig. 2, respectively. The unit of the track irregularity is mm.

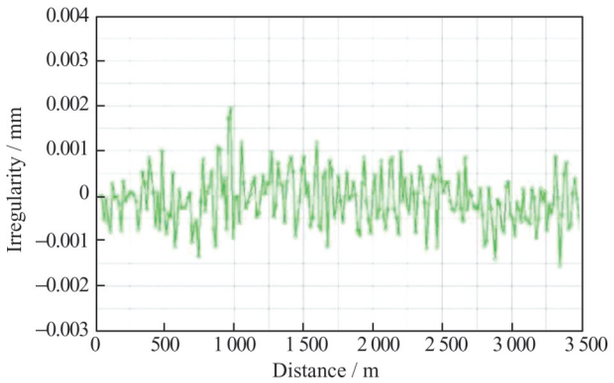



**Fig. 2 The lateral right track irregularities**

### 1.3 Combined Simulation Under MATLAB/Simulink Environment

This study used VI-Rail and MATLAB/Simulink to complete the co-simulation process. By receiving the dynamic variables of the VI-Rail model, Simulink evaluates the control law from the dynamic variables returned by the VI-Rail model and feeds the resulting damping force back into the model in real time. Figs. 3 and 4 show the co-simulation process.

Based on the previous VI-Rail model of CRH2C electric multiple units (EMU) and its speed of 70 m/s with specific track irregularities, the fundamental algorithm relies on the utilisation of an on-off hybrid control method. The maximum damping coefficient is 8 000 N·s/m. The damping coefficient at its least value is 400 N·s/m. The logic diagram of hybrid semi-active control strategy and the logic diagram of subsystem are shown in Fig. 3 and Fig. 4.

In Fig. 3 and Fig. 4, $a$ equals the weighting factor $\alpha$. The velocity of the car body is denoted as $v1$. The ve-

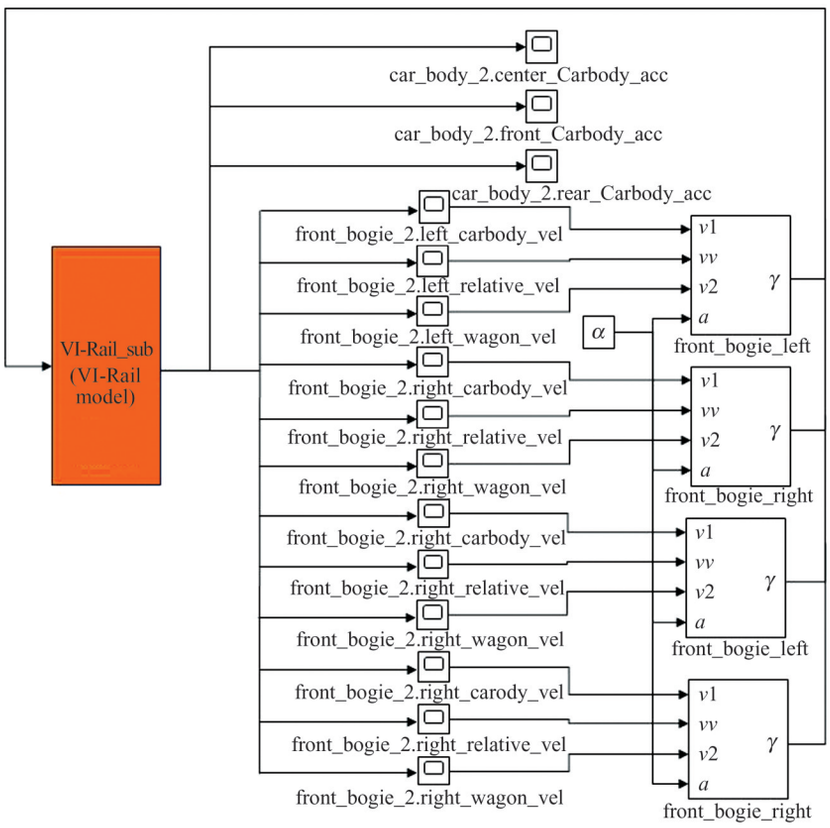



**Fig. 3 Logic diagram of hybrid semi-active control strategy**

locity of the bogie system is denoted as $v2$. The variable $vv$ represents the velocity of the car body in relation to the bogie system. The modulation coefficient of the Sky-hook control is denoted as $y1$. The coefficient of damping for the Groundhook control is denoted as $y2$. The damping coefficient of the hybrid control is denoted as $y$.

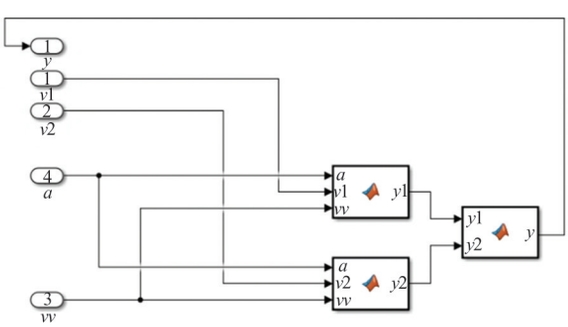



**Fig. 4 Logic diagram of subsystem**

## 2 Results

The acceleration of the car body was categorized into two distinct components: front acceleration and rear acceleration. During the following co-simulation, these parts of the carriage will not deform. As a result, in the following research, this study will concentrate on the lateral acceleration of the rear bogie system, as shown in Figs. 5-7. The co-simulation of this research utilised various parameters $\alpha$ to simulate the situation of accelerations of the front bogie and rear bogie under the hybrid control strategy and gathered the data, which are shown in Fig. 5 to Fig. 7. When $\alpha$ varies from 0 to 1 under the Hybrid control suspension, the maximum, minimum and root mean square (RMS) of the collected lateral acceleration are shown in Table 1.

The relative change in RMS listed in Table 1 is employed to compare the hybrid control and the passive control configurations; it is defined as the percentage difference of the RMS lateral acceleration with respect to the passive suspension, and a negative value indicates that the hybrid control suppresses lateral vibration more effectively than the passive suspension. This study selected the front and rear car body acceleration with a greater peak value and a smaller relative change in RMS to obtain more precise findings. With an increase in $\alpha$, the lateral acceleration of the car body decreases. When $\alpha$ falls within the range of 0.9-1.0, the hybrid control

**Table 1 Comparison of lateral acceleration indices of different control strategies**

| Control strategies | Maximum acceleration/$(m \cdot s^{-2})$ | Minimum acceleration/$(m \cdot s^{-2})$ | RMS/$(m \cdot s^{-2})$ | Relative change in RMS/% |
|---|---|---|---|---|
| Passive | 0.962 377 | −0.897 68 | 0.235 89 | — |
| $\alpha$ =0.0 (Groundhook) | 0.901 42 | −0.914 25 | 0.262 547 | 11.3 |
| $\alpha$ =0.1 | 0.874 262 | −0.895 47 | 0.254 035 | 7.7 |
| $\alpha$ =0.2 | 0.828 58 | −0.859 36 | 0.248 921 | 5.5 |
| $\alpha$ =0.3 | 0.863 675 | −0.834 59 | 0.244 823 | 3.8 |
| $\alpha$ =0.4 | 0.863 675 | −0.834 59 | 0.244 823 | 3.8 |
| $\alpha$ =0.5 | 0.878 186 | −0.878 29 | 0.253 608 | 7.5 |
| $\alpha$ =0.6 | 0.885 971 | −0.879 74 | 0.242 064 | 2.6 |
| $\alpha$ =0.7 | 0.884 489 | −0.879 17 | 0.238 481 | 1.1 |
| $\alpha$ =0.8 | 0.880 991 | −0.880 08 | 0.234 367 | −0.6 |
| $\alpha$ =0.9 | 0.874 925 | −0.866 07 | 0.228 796 | −3.0 |
| $\alpha$ =1.0 (Skyhook) | 0.845 479 | −0.913 08 | 0.223 972 | −5.1 |

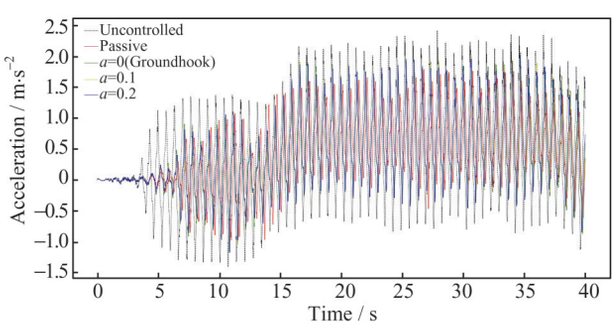



**Fig. 5 Car body lateral acceleration using passive control and hybrid control with $\alpha$ ranging from 0.0 to 0.2**

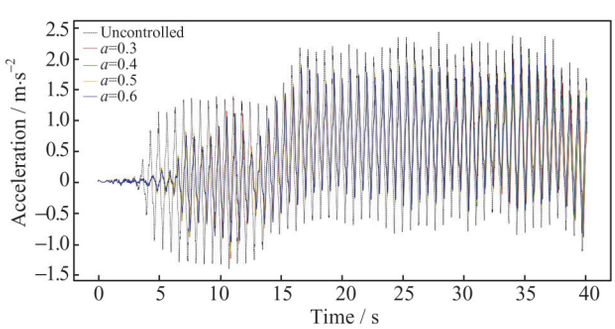



**Fig. 6 Car body lateral acceleration using passive control and hybrid control with $\alpha$ ranging from 0.3 to 0.6**

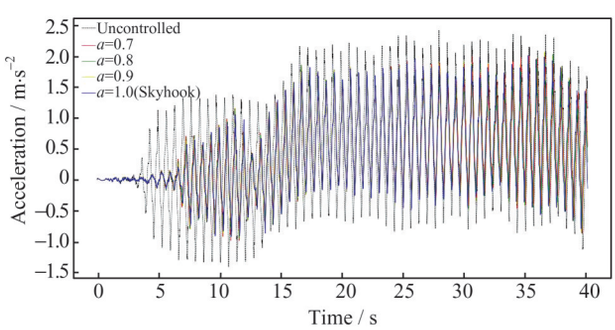



**Fig. 7 Car body lateral acceleration using passive control and hybrid control with $\alpha$ ranging from 0.7 to 1.0**

technique exhibits greater efficacy in mitigating lateral vibration in comparison with the passive suspension.

## 3 Conclusion

This passage incorporates vehicle data from the Hexie (Harmony) CRH2C EMU with the goal of improving the riding comfort of high-speed train operations at a commercial speed of 70 m/s. Utilizing principles of vehicle dynamics theory, a corresponding vehicle dynamics model is established, capturing the intri-

cate interactions between various components of the vehicle system. Furthermore, the integration of established Skyhook and Groundhook control theories is accomplished by meticulously adjusting the weighting parameter $\alpha$, hence enabling accurate regulation of the suspension system. The implementation of the vehicle dynamics model within the VI-Rail software environment has proven to be successful, offering a reliable platform for the purposes of research and simulation. Through joint simulation using MATLAB/Simulink, the dynamic behaviour of the model under different operating conditions is thoroughly investigated, enabling a comprehensive evaluation of ride comfort and stability. The main conclusions are summarised as follows:

The hybrid control approach is capable of mitigating the lateral vibration of the high-speed vehicle by the adjustment of the weighting parameter $\alpha$. When the weighting parameter $\alpha$ falls within the range of 0.9-1.0, the restriction to lateral vibration is superior to passive control, resulting in enhanced riding comfort.

At a speed of 70 m/s (252 km/h), to restrict the lateral vibration and improve riding comfort, the weighting parameter $\alpha$ for hybrid control should be in the range of 0.9 to 1.0. When the weighting parameter $\alpha$ is over this critical value, the riding comfort of hybrid control can be ensured compared with the passive control suspension.

The vehicle dynamics model is established under the VI-Rail environment and co-simulated with MATLAB/Simulink. In addition, the stability of the model was verified.

## References


[1] Sun Y, Zhou J S, Gong D, *et al*. A new vibration absorber design for under-chassis device of a high-speed train[J]. *Shock and Vibration*, 2017, **2017**(1): 1523508.

[2] Qin Z, Zhou S, Sun C, *et al*. Influence of hydraulic shock absorber characteristic parameters on the critical speed of high-speed trains[J]. *Journal of Mechanical Engineering*, 2017, **53**(6): 138-144.

[3] Jin T H, Liu Z M, Sun S S, *et al*. Development and evaluation of a versatile semi-active suspension system for high-speed railway vehicles[J]. *Mechanical Systems and Signal Processing*, 2020, **135**: 106338.

[4] Li P S, Lam J, Cheung K C. Multi-objective control for active vehicle suspension with wheelbase preview[J]. *Journal of Sound and Vibration*, 2014, **333**(21): 5269-5282.

[5] Karnopp D. Active and semi-active vibration isolation[J]. *Journal of Mechanical Design*, 1995, **117**: 177-185.

[6] Han J, Hayashi Y, Jia P, *et al*. Economic effect of high-speed rail: Empirical analysis of Shinkansen's impact on industrial location[J]. *Journal of Transportation Engineering*, 2012, **138**(12): 1551-1557.

[7] Poussot-Vassal C, Spelta C, Sename O, *et al*. Survey and performance evaluation on some automotive semi-active suspension control methods: A comparative study on a single-corner model[J]. *Annual Reviews in Control*, 2012, **36**(1): 148-160.

[8] Dong X M, Yu M, Li Z S, *et al*. A comparison of suitable control methods for full vehicle with four MR dampers, part I: Formulation of control schemes and numerical simulation [J]. *Journal of Intelligent Material Systems and Structures*, 2009, **20**(7): 771-786.

[9] Guo J. *Research on Control Strategy for High-Speed Train Semi-Active Suspension System*[D]. Hangzhou: Zhejiang University, 2017(Ch).

[10] Leblebici A S, Türkay S. Hybrid control for semi-active suspension design of a railway vehicle[C]//2020 21*st International Carpathian Control Conference* (*ICCC*). New York: IEEE, 2020: 1-6.

[11] Díaz-Choque C S, Félix-Herrán L C, Ramírez-Mendoza R A. Optimal skyhook and groundhook control for semiactive suspension: A comprehensive methodology[J]. *Shock and Vibration*, 2021, **2021**(1): 8084343.

[12] Guo K, Sui J, Guo Y. Semi-active control method for a high-speed railway vehicle lateral damper based on skyhook and groundhook hybrid damping[J]. *Journal of Vibration and Shock*, 2013, **32**(2): 18-23.

[13] Guo J, Xu Z G, Sun Y X. A new semi-active safety control strategy for high-speed railway vehicles[J]. *Vehicle System Dynamics*, 2015, **53**(12): 1918-1934.

[14] Zhao Y W, Liu Y Q, Yang S P, *et al*. A new coordination control strategy on secondary lateral damper for high-speed trains[J]. *Journal of Vibration Engineering & Technologies*, 2022, **10**(1): 395-408.

[15] Liu C N, Chen L, Lee H P, *et al*. Generalized skyhook-groundhook hybrid strategy and control on vehicle suspension[J]. *IEEE Transactions on Vehicular Technology*, 2023, **72**(2): 1689-1700.

[16] Savaresi S M, Silani E, Bittanti S. Acceleration-driven-damper (ADD): An optimal control algorithm for comfort-oriented semiactive suspensions[J]. *Journal of Dynamic Systems, Measurement, and Control*, 2005, **127**(2): 218-229.

[17] Yan Z Y, Li G, Luo J, *et al*. Vibration control of supercon-

ducting electro-dynamic suspension train with electromagnetic and skyhook damping methods[J]. *Vehicle System Dynamics*, 2022, **60**(10): 3375-3397.

[18] Zhai W M, Liu P F, Lin J H, *et al*. Experimental investigation on vibration behaviour of a CRH train at speed of 350 km/h[J]. *International Journal of Rail Transportation*, 2015, **3**(1): 1-16.

# 高速铁路车辆半主动悬挂混合控制策略与建模：以CRH2C动车组为例

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**摘要：**针对高速动车组提速后车辆横向振动加剧、乘坐舒适性下降的问题，本文以 CRH2C 动车组为研究对象，在 VI-Rail 环境中建立车辆动力学模型，并与 MATLAB/Simulink 进行联合仿真，提出一种基于 Skyhook 与 Groundhook 的半主动悬挂混合控制策略，以权重因子 $\alpha$ 调节两种控制策略的作用权重。针对德国标准线性低不平顺谱轨道、列车以 70 m/s（252 km/h）运行的工况，以车体横向加速度峰值与均方根值为评价指标，对比混合控制与被动控制的效果。结果表明：当 $\alpha$ 取 0.9~1.0 时，混合控制抑制横向振动的效果优于被动控制，车体横向加速度均方根值最大降低约5.1%；当 $\alpha$ 趋近于 0（趋于纯 Groundhook 控制）时反而不及被动控制。该策略可在不改变车辆结构的前提下改善高速动车组乘坐舒适性，工程应用中权重因子宜取 0.9~1.0。

**关键词：**高速铁路；半主动悬挂；混合控制策略；VI-Rail；MATLAB/Simulink

□