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Active Displacement Control of Pantograph-catenary System for a Half-body Railway Model

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Abstract

The pantograph is an essential component that provides electrical contact between the overhead wires and the electric train. The quality of the current collection in high-speed trains is directly influenced by the mechanical interaction between the pantograph collector head and the overhead contact line. To overcome these challenges and improve pantograph performance, researchers and engineers have explored innovative solutions, including the introduction of active control mechanisms. Excitation by the vehicle is one of the normal disturbances in the dynamic interaction of the pantograph and the overhead line. The vertical effects of vehicle-track vibrations on the interaction between the pantograph and the overhead contact line have not yet been adequately researched. To fill this research gap, this study establishes models for both the pantograph-catenary interaction and the vehicle-track system. In this study, the performance of the modified Skyhook-Proportional-Integral-Derivative (PID) controller was investigated for a half-body of a railway pantograph-catenary system. Track irregularities such as step, sine, and random were applied to perturb the suspension system. The performance of both passive and active systems was investigated by considering the track irregularities as a basis. The root mean square analysis (RMS) found that active displacement control of pantograph-catenary systems for a half-body railway model equipped with modified Skyhook-PID controllers performed better than the passive systems. In summary, the future experimental approach for active half-body railway model could incorporate this simple modification of the Skyhook-PID controller.

Keywords

high-speed trains, pantograph-catenary interaction, vehicle-track system, modified Skyhook-PID

1 Introduction

In today's world, railway pantographs play a critical role in maintaining uninterrupted electrical contact between trains and overhead lines or catenary wire for efficient and safe transportation. These complex systems are acted upon by numerous dynamic forces and environmental factors that can lead to undesirable phenomena such as excessive displacement, vibration, and even disengagement of the overhead line (Xia et al., 2021). The fundamental investigation of the dynamics in interconnected systems within high-speed trains is becoming increasingly important in both industry and academia due to the critical role these systems play in the safe and reliable operation of high-speed trains (Vu etal., 2021). The pantograph overhead contact line system has a prominent role within the rail vehicle system. This is mainly due to the fact that reliable current collection ensures both the safety and stability of high-speed train operation and is a prerequisite for train acceleration (Koutsoloukas et al., 2022). Optimal contact between the pantograph and the overhead contact line is of immense importance to ensure a consistent and reliable electrical power provision for high-speed trains through the catenary wires (Fu et al., 2020). Fig. 1 shows the pantograph-catenary system which consists of two main components: the pantograph, which is located on the roof of the rail vehicle, and the overhead line, which is installed along the rail track. This system plays a crucial role in supplying power to the high-speed train. The electric current is transmitted from the

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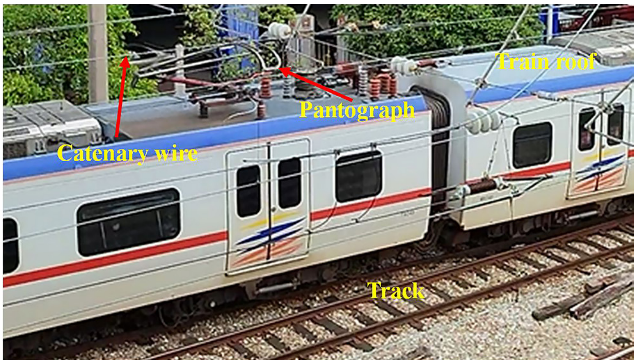

Fig. 1 Pantograph catenary system in operating train

contact wire to the train via the current collector. The contact between the pantograph strip and the catenary wire is the only source of electricity for the high-speed train. As noted in previous research, loss of contact would result in an inadequate power supply to electric train, causing disruptions in acceleration, braking, and communications. Another consideration is that if the contact force is too high, there would be significant arcing or rapid wear of both the pantograph and the overhead contact line, which would significantly shorten the life of the entire system (Németh and Gáspár, 2010). Therefore, it is imperative to maintain an adequate contact between the pantograph and the overhead line. Several models have been developed to explain the complex coupling dynamics behavior of the pantograph-catenary system and for ensuring a stable contact between them (Song et al., 2021a). Long-term evolution of the catenary modeling methodology ranges from a simple model (Antunes et al., 2020) to an increasingly complex model (Pombo and Ambrósio, 2013). Since it is an effective representation of physical properties, the pantograph is usually modeled as 2DOF or 3DOF of pantograph model connected by appropriate springs and dampers (Simarro et al., 2020). Advanced multi-body models for pantographs that can better represent realistic behavior are currently being developed by several researchers (Abdullah et al., 2010; Pombo and Ambrósio, 2012). The effectiveness of simulation models is significantly increased when cutting-edge numerical approaches are used (Song et al., 2019; Song et al., 2020). Comparison of the accuracy of the proposed models with experimental data from laboratory (Karakose and Yaman, 2020; Subki et al., 2021) and field experiments (Shih et al., 2021; Wang et al., 2020) provides evidence of their accuracy. The quality of current collection can be improved based on the simulation results using a number of practical methods, for example by adjusting the contact wire tension (Chu and Song, 2020), optimizing the pantograph interval (Shaltout et al., 2022), modifying the pantograph's suspension parameters (Veluvolu et al., 2022), and using an active pantograph with dampers (Jiao et al., 2020). Rather than that many researchers use various controllers for decreasing fluctuation in the contact force such as genetic algorithm with proportional-integral-derivative controller (Al-Awad et al., 2021), single input fuzzy logic controller (Farhan Kamerul Bieza et al., 2019), proportional-integral-derivative controller (Ko et al., 2017; Sanchez-Rebollo et al., 2013; Zdziebko et al., 2019) and multi-objective H_∞ controller (Lu et al., 2018). The works of these authors deserve attention when considering the effect of vehicle track excitations in conjunction with a spatial contact model that accounts for the interaction between the contact wire and the pantograph strip (Song, et al., 2021b). Several researchers have reported that mathematical modeling proved to be an effective approach in capturing the complex dynamic behavior of the pantograph system because of the high cost of field testing (Pham et al., 2022; Song and Li, 2021; Yu et al., 2021). However, it is found that the dynamic behavior of the pantograph system is limited when vehicle-track disturbances are considered. For instance, Song and Duan (2022) reported in their article on the dynamic behavior of the pantograph and overhead contact line under random disturbances of the vehicle track that the vertical vibrations of the car body have the greatest influence on the interaction between the pantograph and overhead contact line. Therefore, the primary objective of this research work is to develop a half-body railway model specifically designed for vertical dynamic railway systems. In this paper, simulation results on the strategy of active displacement control to enhance the quality of contact in the interaction between the pantograph and the catenary wire are presented. The investigation focused on evaluating the performance of those controllers which are proportional-integral-derivative (PID), Skyhook-PID, and modified Skyhook-PID controllers regarding vertical displacement for a half-body railway pantograph model. The study introduces the concept of active displacement control, which aims to minimize the vertical displacement of the half-body railway pantograph systems. Excessive displacement can lead to problems such as poor contact quality, increased component wear, and lower energy efficiency.

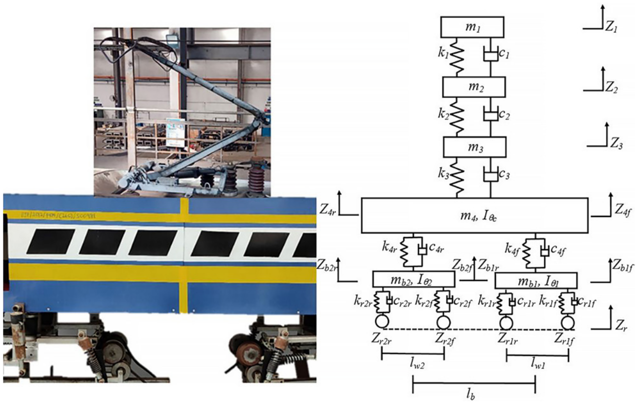

Fig. 2 Physical 9 DOF model of the passive system

2 Simplified Pantograph-Catenary Model

In this study, a half-body with nine degrees of freedom (9 DOF) of the railway pantograph system is considered. Fig. 2 shows the basic of a half-body railway model, which consists of a 3DOF pantograph model with three moving masses; contact strip, m_1, pan-head, m_2, and frame, m_3, which can move in the uplifts Z_1, Z_2, Z_3 respectively. 6 DOF car model with another three masses in motions; car body, m_4, which can move in the directions of uplift Z_4 and pitch θc. Two bogies, mb_1 and mb_2 that can bounce and pitch with Z_{b1f}, Z_{b1r}, Z_{b2f}, Z_{b2r}, θ_1, θ_2 respectively and four rigid wheelsets. There are spring-damper elements (k_1, k_2, k_3, c_1, c_2, c_3) between m_1 and m_2, m_2 and m_3, as well as be-tween m_3 and car body m_4. A secondary suspension system, consisting of a parallel configuration of spring and damper pairs (k_{4r}, k_{4f}, c_{4r}, c_{4f}), is installed between the car body and the bogie frame. The bogie frame, which includes two wheelsets, is connected to the wheelsets through a primary suspension system comprising pairs of springs and dampers (k_{b1r}, k_{b1f}, k_{b2r}, k_{b2f}) (c_{b1r}, c_{b1f}, c_{b2r}, c_{b2f}). For analysis purposes, the contact wire is modeled as a basic spring and damper system. The physical parameters used are shown in Table 1 (Abdullah et al., 2013; Xia et al., 2000).

3 Controller design

Fig. 3 shows the 9 DOF model of the active pantograph with secondary suspension control. The secondary suspension control inputs are denoted by f_{ar} and f_{af}, pantograph control with f_{sky} and track irregularities are denoted as Z_{r1r}, Z_{r1r}, Z_{r2r} and Z_{r2f} respectively.

Assuming small motions, the linearized dynamic equations for the primary and secondary suspensions and the dynamic equations governing the motion of the pantograph can be described by Eq. (1) to Eq. (9). While Eq. (10)

Table 1 The parameters of 9 DOF system

Parameter	Value	Units
m_1	12	kg
m_2	5	kg
m_3	10.38	kg
m_4	50990	kg
m_{b1}, m_{b2}	4360	kg
k_1	32992	N m^{-1}
k_2	14544	N m^{-1}
k_3	611.85	N m^{-1}
k_{4r}, k_{4f}	1060000	N m^{-1}
k_{b1r}, k_{b1f}, k_{b2r}, k_{b2f}	2976000	N m^{-1}
c_1	12.31	Ns m^{-1}
c_2	0.11	Ns m^{-1}
c_3	50.92	Ns m^{-1}
c_{4r}, c_{4f}	30000	Ns m^{-1}
c_{b1r}, c_{b1f}, c_{b2r}, c_{b2f}	15000	Ns m^{-1}
$I_{\theta c}$	1875300	kg m^2
$I_{\theta 1}$, $I_{\theta 2}$	5070	kg m^2
l_b	15.6	m
l_{w1}, l_{w2}	2.5	m

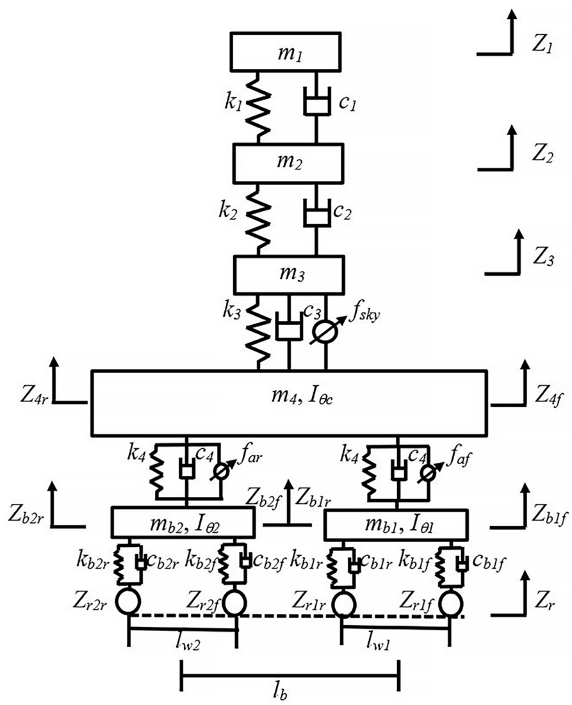

Fig. 3 9 DOF model of the active pantograph with secondary suspension control

and Eq. (11) show the decoupling transformation equations for generating two single actuator forces (f_{ar}, f_{af}) and moments (m_p). The widely used skyhook control approach is derived from an imaginary damper attached to the sky, as shown in Eqs. (12) and (13) is the modified skyhook equation. The system was given a step input of 0.05 m with a sampling time of 0.1 s, the inputs consist of a sinusoidal signal with an amplitude of 0.05 at a frequency of 2π and a random signal ranging from –0.05 m to 0.05 m. These inputs are assumed to be directly transmitted from the track to the car body and subsequently to the pantograph support, exerting a specific force upon reaching the support.

$$m_{b1}\ddot{z}_{b1} = k_{b1r}\left(z_{r1r} - z_{b1r}\right) + c_{b1r}\left(\dot{z}_{r1r} - \dot{z}_{b1r}\right) + k_{b1f}\left(z_{r1f} - z_{b1f}\right) + c_{b1f}\left(\dot{z}_{r1f} - \dot{z}_{b1f}\right) - k_{4f}\left(z_{b1} - z_{4f}\right) - c_{4f}\left(\dot{z}_{b1} - \dot{z}_{4f}\right) + f_{af} \quad (1)$$

$$\ddot{\theta}_{b1}I_{b1} = \frac{l_{w1}}{2}\left[k_{b1f}\left(z_{r1f} - z_{b1f}\right) + c_{b1f}\left(\dot{z}_{r1f} - \dot{z}_{b1f}\right)\right] - \frac{l_{w1}}{2}\left[k_{b1r}\left(z_{r1r} - z_{b1r}\right) + c_{b1r}\left(\dot{z}_{r1r} - \dot{z}_{b1r}\right)\right] \quad (2)$$

$$m_{b2}\ddot{z}_{b2} = k_{b2r}\left(z_{r2r} - z_{b2r}\right) + c_{b2r}\left(\dot{z}_{r2r} - \dot{z}_{b2r}\right) + k_{b2f}\left(z_{r2f} - z_{b2f}\right) + c_{b2f}\left(\dot{z}_{r2f} - \dot{z}_{b2f}\right) - k_{4r}\left(z_{b2} - z_{4r}\right) - c_{4r}\left(\dot{z}_{b2} - \dot{z}_{4r}\right) + f_{ar} \quad (3)$$

$$\ddot{\theta}_{b2}I_{b2} = \frac{l_{w2}}{2}\left[k_{b2f}\left(z_{r2f} - z_{b2f}\right) + c_{b2f}\left(\dot{z}_{r2f} - \dot{z}_{b2f}\right)\right] - \frac{l_{w2}}{2}\left[k_{b2r}\left(z_{r2r} - z_{b2r}\right) + c_{b2r}\left(\dot{z}_{r2r} - \dot{z}_{b2r}\right)\right] \quad (4)$$

$$\ddot{z}_4 m_4 = k_{4r}\left(z_{b2} - z_{4r}\right) + c_{4r}\left(\dot{z}_{b2} - \dot{z}_{4r}\right) + k_{4f}\left(z_{b1} - z_{4f}\right) + c_{4f}\left(\dot{z}_{b1} - \dot{z}_{4f}\right) - k_3\left(z_4 - z_3\right) - c_3\left(\dot{z}_4 - \dot{z}_3\right) - f_{sky} + f_{ar} + f_{af}. \quad (5)$$

$$\ddot{\theta}_c I_c = \frac{l_b}{2}\left[k_{4f}\left(z_{b1} - z_{4f}\right) + c_{4f}\left(\dot{z}_{b1} - \dot{z}_{4f}\right)\right] - \frac{l_b}{2}\left[k_{4r}\left(z_{b2} - z_{4r}\right) + c_{4r}\left(\dot{z}_{b2} - \dot{z}_{4r}\right)\right]. \quad (6)$$

$$\ddot{z}_3 m_3 = k_3\left(z_4 - z_3\right) + c_3\left(\dot{z}_4 - \dot{z}_3\right) - k_2\left(z_3 - z_2\right) - c_2\left(\dot{z}_3 - \dot{z}_2\right) + f_{sky}. \quad (7)$$

$$\ddot{z}_2 m_2 = k_2\left(z_3 - z_2\right) + c_2\left(\dot{z}_3 - \dot{z}_2\right) - k_1\left(z_2 - z_1\right) - c_1\left(\dot{z}_2 - \dot{z}_1\right). \quad (8)$$

$$\ddot{z}_1 m_1 = k_1\left(z_2 - z_1\right) + c_1\left(\dot{z}_2 - \dot{z}_1\right). \quad (9)$$

$$F_{af} = 0.5F_z + \frac{1}{l_b}M_p. \quad (10)$$

$$F_{ar} = 0.5F_z - \frac{1}{l_b}M_p. \quad (11)$$

$$F_{sky} = -c_{sky}\dot{z}_3. \quad (12)$$

$$F_{sky} = c_{sky}\left[\alpha\left(\dot{z}_4 - \dot{z}_3\right) - \left(1 - \alpha\right)\dot{z}_3\right]. \quad (13)$$

Simple control mechanisms such as PID and Skyhook controllers are usually used to control the pantograph system. An automatically tuning method is employed to tune the PID controller, where the controller parameters are automatically adjusted to effectively counteract disturbances. The simulation results are evaluated using the root mean square and the percentage improvement method. The root mean square (RMS) for a set of N values, which includes $\{x_1, x_2, x_3, \dots x_n\}$, can be calculated using Eq. (14). The percentage of improvement was determined using Eq. (15). Tables 2 to 4 below provide a summary of the optimal combination of P, I, and D values for every input and controller.

$$x_{rms} = \sqrt{\frac{\left(x_1^2 + x_2^2 + x_3^2 + \dots x_n^2\right)}{N}}. \quad (14)$$

$$\%\ improve = \left|\frac{offset_{passive} - offset_{active}}{offset_{passive}}\right| \times 100. \quad (15)$$

4 Results and discussion

All figures below show the comparison of the results of different configurations: active pantograph with PID controller, skyhook-PID controller, modified skyhook-PID controller, and passive system. The performance of

Table 2 The optimal combination of P, I, D values for both actuators

Constant	Input
k_P	1.4 × 10^7
k_I	3.2 × 10^7
k_D	1.3 × 10^6
Filter coefficient (N)	3.2 × 10^3

Table 3 The optimal combination of Skyhook-P, I, D values

Constant	Input
k_P	−31.82
k_I	−527.17
k_D	−0.126
Filter coefficient (N)	39.94

Table 4 The optimal combination of Modified Skyhook-P, I, D values

Constant	Input
k_P	37.79
k_I	1194.25
k_D	−0.3384
Filter coefficient (N)	88.65

the passive system is shown by a blue solid line, while the active system with a PID controller is shown by a red dashed line. The Skyhook-PID controller is represented by a green dashed-dotted line, and the modified Skyhook-PID controller is represented by a black dotted line.

As shown in Fig. 4(a)–(c) the input such as step, sine and random representing the track irregularities was given to the system at front wheel Z_{rlf}. Figs 5 to 7 show the output responses of the vertical displacement of the contact strip for each system under different input perturbations, namely step, sine, and random. From the graph, it is shown that the system comes to the level condition at two seconds after the input given at one second for active system compared to the passive system where the vehicle remained declined at 0.02 m height of displacement.

The results for RMS value and percentage of improvement under different inputs are presented in Table 5. Noted that the lower values of RMS indicate better fit

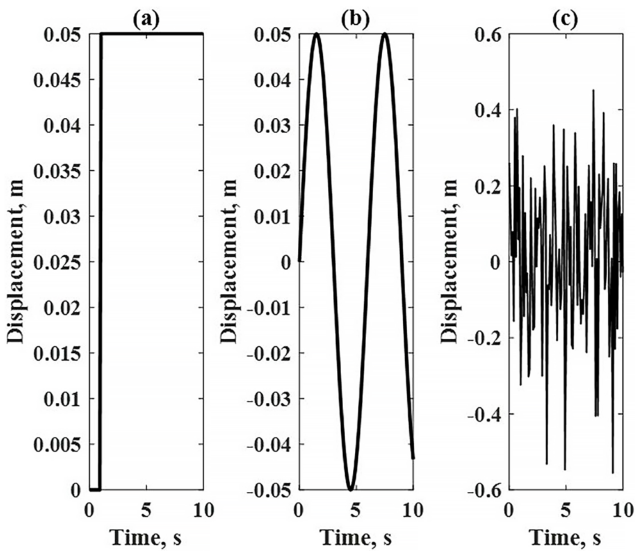

Fig. 4 Input at Z_{rlf} (a) Step; (b) Sine; (c) Random

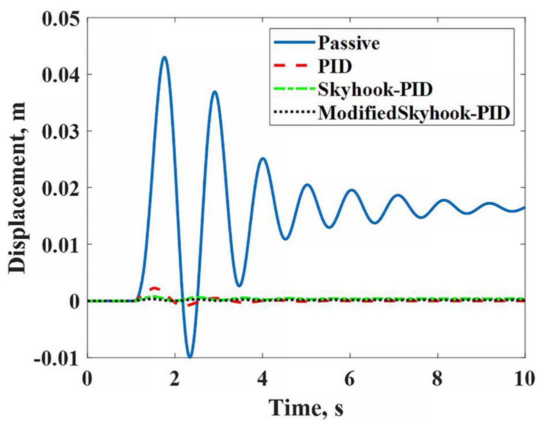

Fig. 5 Output responses of the vertical displacement for the step input

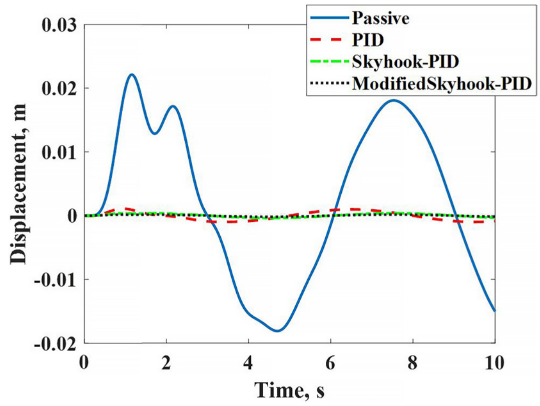

Fig. 6 Output responses of the vertical displacement for the sine input

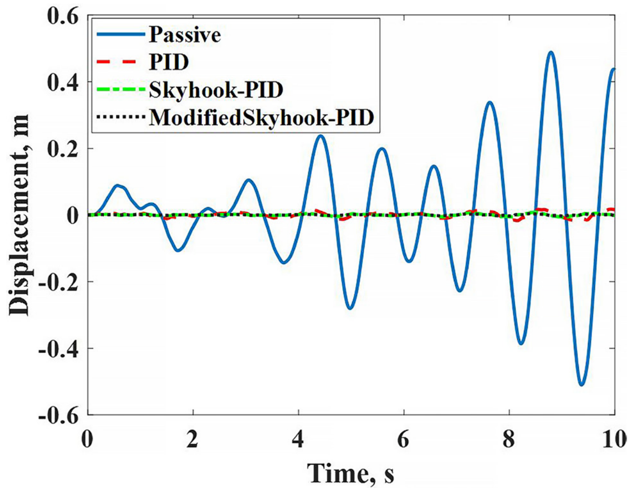

Fig. 7 Output responses of the vertical displacement for the random input

Table 5 The RMS value under varies input for each system

Input	System	RMS	Improve (%)
Step	Passive	1.7×10^{-2}	–
	PID	4.9×10^{-7}	99.997
	Skyhook-PID	3.7×10^{-4}	97.769
	Modified Skyhook-PID	1.6×10^{-4}	99.008
Sine	Passive	1.5×10^{-2}	–
	PID	8.5×10^{-4}	94.378
	Skyhook-PID	3.2×10^{-4}	97.848
	Modified Skyhook-PID	1.5×10^{-4}	99.006
Random	Passive	4.3×10^{-1}	–
	PID	1.6×10^{-2}	96.403
	Skyhook-PID	1.9×10^{-3}	99.566
	Modified Skyhook-PID	1.6×10^{-3}	99.629

of the proposed controller. Although the improvement on the displacement is minor, the contact quality noticeably improved in comparison to the passive system. From Table 5 it was concluded that after the system which was assumed to be an active system after applying the controller, the performance of displacement of half body railway pantograph showed an improvement of above 95%. The active system indicated a better performance as compared to the passive when the train was disturbed by track irregularities.

5 Conclusion

In conclusion, the modified Skyhook PID controller was successfully implemented in an active displacement control for a half-body railway pantograph system in a simulation study. Throughout the study, a simple method was used to tune the PID controller in this system. The active displacement control isolates the effects of track irregularities from the wheelset and maintains the vertical displacement at a level of approximately zero. This is evidenced by the lowest RMS value achieved and the highest percent improvement value. The modified Skyhook PID controller performs well for both sinusoidal and random disturbances and the performance of the PID controller has been demonstrated to be superior when the system is subjected to a step input disturbance. The results of the performance analysis of the controller show the potential of a simple modification of the Skyhook-PID controller for future experimental approaches to an active half-body railway model.

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