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Robust Control of Pantograph–Catenary Contact Force Under High Disturbance: A Comparative Study

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ABSTRACT

This paper presents a comparative study of three control strategies for regulating the contact force in pantograph–catenary systems operating under high disturbances and nonlinear dynamics. A high-fidelity multi-layer physical model is developed to capture key system behaviors, including severe catenary oscillations and variations in pantograph mass. The evaluated control methods include: (1) Sliding Mode Control (SMC) augmented with a state observer, (2) observer-free SMC incorporating input signal filtering, and (3) classical PID control with low-pass filtering. Simulation results show that the observer-free SMC achieves the best overall performance, exhibiting strong robustness, minimal force deviation, and high stability under both dynamic scenarios. In contrast, the observer-based SMC suffers from estimation-induced lag, while the PID controller becomes unstable under severe conditions. The findings suggest that observer-free SMC with filtering is highly suitable for real-time implementation in high-speed rail systems, where resilience, simplicity, and computational efficiency are critical.

Keywords: Pantograph–Catenary System, Sliding Mode Control, State Observer, PID Control, Contact Force Regulation, High-Speed Rail, Robust Control, Simulation, Railway Electrificatio.

INTRODUCTION

The pantograph–catenary system plays a vital role in maintaining continuous electrical contact between a moving electric train and the overhead power lines. Ensuring the stability and quality of this interaction is particularly crucial in high-speed railway operations, where the dynamics become highly nonlinear, time-varying, and susceptible to strong mechanical disturbances. One of the key performance indicators of such systems is the ability to regulate the contact force between the pantograph and the catenary wire. This force must be maintained within a narrow optimal range: too low a force risks loss of contact and arcing, while excessive force can cause accelerated wear, mechanical fatigue, and even system damage. The challenge becomes even more prominent under conditions of rapid acceleration, crosswinds, or infrastructural irregularities such as support pole spacing or catenary sag. These factors make it difficult to maintain smooth and continuous power transfer, especially when the system is subject to actuator delays, structural flexibilities, and unmodeled nonlinearities.

Conventional control strategies, particularly the Proportional–Integral–Derivative (PID) controller, have been widely adopted in early pantograph–catenary systems due to their simplicity, rapid response, and ease of tuning [1]. Despite their popularity, PID-based controllers face challenges in dynamic environments such as high-speed rail, where nonlinearities, actuator delays, and time-varying disturbances are prevalent [2]. This results in degraded tracking of the contact force and an increased risk of arcing or mechanical damage at high velocities. To enhance robustness and performance, Model Predictive Control (MPC) has gained traction due to its capacity to incorporate constraints and predict future behaviours over a moving horizon [3], [4]. While some research has successfully applied MPC to pantograph control [5], its high computational complexity and real-time demand often render it unsuitable for embedded applications operating at millisecond-level sampling rates [6]. Researchers have also investigated intelligent and adaptive control methods, such as fuzzy logic control [7] and adaptive neuro-fuzzy inference systems (ANFIS) [8]. These methodologies have shown enhanced performance in uncertain and nonlinear environments. However, they often rely on empirical rule bases, necessitate extensive tuning, and offer limited theoretical stability guarantees. Sliding Mode Control (SMC) has arisen as a promising solution due to its inherent

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robustness against disturbances, parametric uncertainties, and modelling errors [9]. SMC enforces finite-time convergence of tracking errors while maintaining stability under bounded uncertainties. Variants such as second-order SMC and super-twisting algorithms issue chattering, a common drawback in basic SMC. Nevertheless, performance may deteriorate when full-state information is unavailable or compromised. To address observability limitations, many studies incorporate state observers, including Extended Kalman Filters (EKF), Sliding Mode Observers (SMO), or Luenberger observers to reconstruct unmeasured states [10], [11]. These observer-based SMC systems aim to diminish sensor dependency while enhancing robustness. For instance, Bartos and Kuchta [12] applied SMO to pantograph systems to estimate dynamic contact force. Corradini et al. [13] employed disturbance observers to estimate unmodelled dynamics in the pantograph–catenary contact. Despite their advantages, these methods are vulnerable to estimation delays and modelling mismatches, especially under rapid disturbances and nonlinear transitions. Another study [14] compared 1-DOF and 2-DOF control structures for active pantograph control and concluded that system robustness heavily relies on estimation quality. In [15], a robust control scheme was proposed using a lumped-mass catenary model and a disturbance observer, but practical implementation challenges remained due to model complexity. Key research [16] developed output feedback control using adaptive observers for partially known pantograph–catenary dynamics but encountered real-time tracking errors due to estimation delays during rapid transients. Another study [17] combined Sliding Mode Control (SMC) with fuzzy logic to improve robustness but overlooked actuator delays and filtered force feedback. In contrast, [18] demonstrated that simple low pass filters significantly enhance force tracking in robotic systems, highlighting their potential for pantograph applications. Moreover, as highlighted by Giry et al. (2015) [19], real-time implementation of sophisticated observers in railway systems requires cautious trade-offs between performance and computational feasibility. To address these limitations, some studies have shifted toward hybrid or observer-free control strategies. For example, Bonomo et al. (2020) [20] evaluated low pass filtered feedback in active pantograph control and found that filtering effectively suppresses noise without affecting response time

Another fundamental reference is the EN 50318:2018 standard [21], which defines validation criteria for pantograph–catenary simulations. It emphasizes both dynamic contact quality and RMS force metrics, reinforcing the need for robust, noise-resilient controllers that meet industry standards for accuracy and operational reliability.

These studies reveal a critical issue: while advanced observers and intelligent controllers' function effectively under ideal conditions, they struggle in fast, noisy, and uncertain environments like high-speed rail. Furthermore, their complexity inhibits real-time implementation.

This paper proposes a robust, simplified control approach for pantograph–catenary force regulation. It integrates filtered force feedback with SMC, omitting state observers, which provides greater simplicity, responsiveness, robustness, and real-time applicability. The proposed observer-free SMC is evaluated against two benchmarks:

- SMC with a state observer.
- Classical PID control with input filtering.

These methods are tested in two challenging scenarios:

- Multi-frequency, high-amplitude catenary disturbances simulating wind, track vibrations, and pole-spacing irregularities.
- Increased pantograph mass representing heavy operational loads or design changes.

This study offers a theoretical advancement by simplifying robust control and presents a practical solution to enhance reliability and real-world deployment of pantograph–catenary systems.

The paper is organized as follows: Section II reviews the literature on pantograph–catenary interaction and highlights the limitations of existing control methods under high disturbances. Section III develops a multi-layer physical model of the pantograph–catenary system, detailing the dynamic equations, parameters, and assumptions. Section IV outlines the design of three control strategies: Sliding Mode Control (SMC) with a state observer, SMC without an observer using low pass filtered feedback, and a PID controller with input filtering. Section V describes the simulation setup, scenarios, and performance evaluation, including comparisons of tracking accuracy, stability, and robustness.

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Section VI concludes with a summary of findings and future research directions, focusing on real-time implementation and scalability.

MULTI-LAYER PHYSICAL MODELING OF PANTOGRAPH-CATENARY SYSTEM

In high-speed railway power supply systems, the stability of the contact force between the pantograph and the catenary is a critical factor ensuring continuous and safe electrical transmission to the train. However, under harsh operating conditions such as speeds exceeding 300 km/h, crosswinds, and track-induced vibrations, the interaction between the pantograph and the catenary becomes highly nonlinear, multivariable, and sensitive to disturbances. As a result, many studies have proposed a multi-layer physical modeling approach to more accurately simulate the system dynamics (Fig 1).

Specifically, the model comprises the following layers: (i) pantograph dynamics including mass, damping, and nonlinear stiffness; (ii) aerodynamic force modeling as a function of train speed and wind; (iii) catenary oscillations, represented using either lumped-mass or finite element methods; (iv) actuator and control system dynamics incorporating time delays and physical constraints; and (v) environmental effects, such as temperature and base excitation. This layered modeling approach enables accurate integration of all key factors affecting the contact force F_c(t) and supports the design of advanced control strategies (Giry et al., 2015; Bonomo et al., 2020; Wu et al., 2019). Moreover, the development of such models aligns with the EN 50318:2018 European standard for pantograph–catenary interaction simulation.

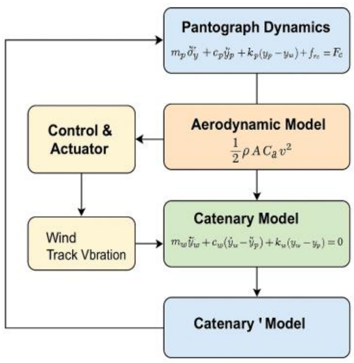

Fig 1. Proposed a multi-layer physical modeling

The interaction between the pantograph and the overhead catenary system is the core of electrical power collection in modern high-speed railways. As shown in Figure 2, this system consists of a pantograph, which is mounted on top of the train, and the contact wire, part of the overhead catenary, which transmits electric current to the vehicle during operation. Understanding this contact mechanism is essential for accurately modeling the contact force F_c(t), which directly affects energy transmission quality, system wear, and safety.

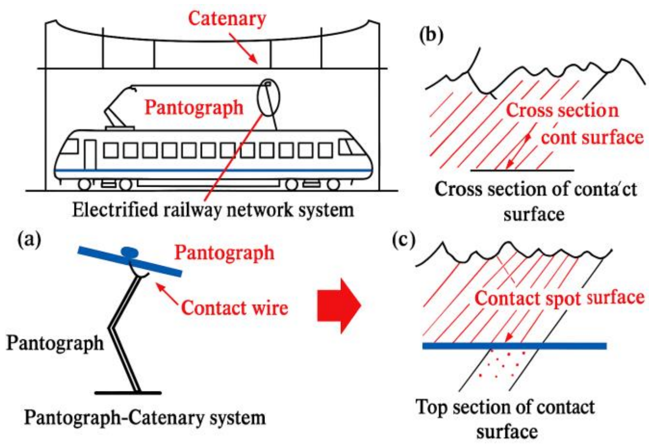

Fig 2. A system consists of a pantograph

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- Figure 2(a) illustrates the general electrified railway network with pantograph–catenary interaction.
- Figure 2(b) shows a zoom-in of the contact interface where the carbon strip of the pantograph touches the contact wire.
- Figure 2(c) presents a cross-sectional view, emphasizing the real surface roughness and the non-ideal micro-contacts formed.
- Figure 2(d) depicts the top view of the contact area, where electrical conduction occurs via discrete contact spots, affected by vibration and surface dynamics.

These physical observations provide the foundation for modeling contact dynamics, such as spring-damper systems and nonlinear friction forces, and justify the need to incorporate multi-layer physical models including aerodynamic disturbance, structural compliance, and dynamic feedback control (Giry et al., 2015; Bonomo et al., 2020; EN 50318:2018).

Designing an accurate controller for a pantograph–catenary system in high-speed railways necessitates a multi-layer physical model that thoroughly represents the factors influencing the contact force F_c(t). Figure 3 depicts the system architecture in layers, systematically capturing the interactions of kinematics, aerodynamics, conductor structure, control–actuation, and environmental effects.

Layer 1: Pantograph Dynamics

The pantograph dynamics are modeled as a second-order mass–spring–damper system with nonlinear friction:

$$F_c = m_p\ddot{y}_p + x_p\dot{y}_p + k_p(y_p - y_w) + \mu.sign(\dot{x_p}) \qquad (1)$$

where: m_p: mass of the pantograph; c_p: damping coefficient; k_p: stiffness of the pantograph linkage; y_p, y_w: positions of pantograph and catenary respectively; $f_{friction}$: dry friction; F_c: contact force.

Layer 2: Aerodynamic Forces

The aerodynamic drag force on the pantograph is given by:

$$F_{aero} = \frac{1}{2}.\rho.A.C_d v^2 \qquad (2)$$

where ρ i sair density, A is frontal area, C_d is drag coefficient, and v is train speed.

Layer 3: Catenary Dynamics

The catenary is modeled using a lumped-mass or finite element approach:

$$m_w\ddot{x}_w + c_w(\dot{x}_w - \dot{x}_p) + k_w(y_w - y_p) = 0 \qquad (3)$$

where m_w is the segment mass, $c_w$is damping, and k_w is the tension-induced stiffness.

Layer 4: Actuator and Control Dynamics

The actuator (servo or pneumatic system) is modeled with delay:

$$\tau_u.\dot{u}(t) + u(t) = u_{ref}(t) \qquad (4)$$

Where: τ_u: actuator time constant; u(t): actuator output force signal; u_{ref} (t): required control signal (from SMC)

Layer 5: Output and Observation

Key outputs are the contact force $F_c(t)$ and pantograph displacement y_p(t). These serve as control references and optimization targets in performance evaluation.

State-space Representation

Chose: $x_1 = y_p$,$x_2 = \dot{y}_p, x_3 = y_w$; $x_4 = \dot{y}_w$; u_{ref}: input signal. d(t): aerodynamic forces or ground vibrations (wind, rail vibration); y(t)= $F_c(t), y_p(t)$: output signal.

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Combining all layers, the system can be formulated in state-space as:

$$\begin{Bmatrix} x(t) = f(x(\dot{t}), u(t), d(t) \\ y(t) = h(x(t) \end{Bmatrix} \tag{5}$$

where $\dot{x}$ (t) includes pantograph and catenary states, $\dot{x}$ (t) $= \begin{bmatrix} y_p \\ \dot{y}_p \\ y_w \\ \dot{y}_w \end{bmatrix}$; $u = u_{ref}$ is the control input, and $d = F_{aero} + Nose$ includes aerodynamic and environmental disturbances.

A powerful force control strategy for pantograph–catenary systems in high-speed rail requires a precise understanding of the key physical and operational factors. The dynamic behaviour of the pantograph, including its mass, damping, and nonlinear stiffness, directly influences the contact force F_c(t). Aerodynamic disturbances generated by high speeds and crosswinds introduce variable external forces that must be addressed. The elastic oscillations and tension dynamics of the catenary wire can result in resonance or wave reflections, thus affecting contact stability. The characteristics of actuators, such as time delays and saturation limits, influence the accuracy and speed of control signal application. Environmental noise arising from track vibrations and temperature fluctuations adds further uncertainty. Accurately modelling these factors is vital for designing robust controllers, such as Sliding Mode Control to ensure that F_c(t) remains within safe operational limits under all conditions.

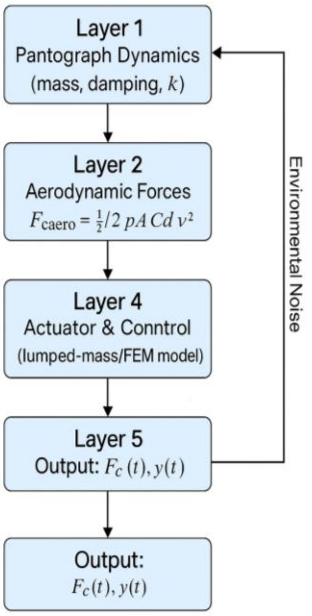

Fig 3. The Multi-layer Physical Modeling of Pantograph–Catenary System

SLIDING MODE OBSERVER FOR MULTI-LAYER PANTOGRAPH–CATENARY MODELING

The interaction between the pantograph and catenary in high-speed railways ensures stable current collection, but it is nonlinear and influenced by uncertainties such as aerodynamics, wire oscillations, and vibrations. Linear control often struggles to maintain a safe contact force F_c(t) due to unmeasured states and sensor noise. We propose a robust control strategy that combines Sliding Mode Control (SMC) and Sliding Mode Observer (SMO) based on a multi-layer model. SMC guarantees finite-time stability and disturbance robustness, while SMO estimates unmeasured states, effectively managing noise and model mismatch. This approach facilitates real-time force control, ensures contact stability, and enhances system resilience for next-generation rail systems. The Pantograph contact force control scheme with SMC combined with SMC observer in Fig 4.

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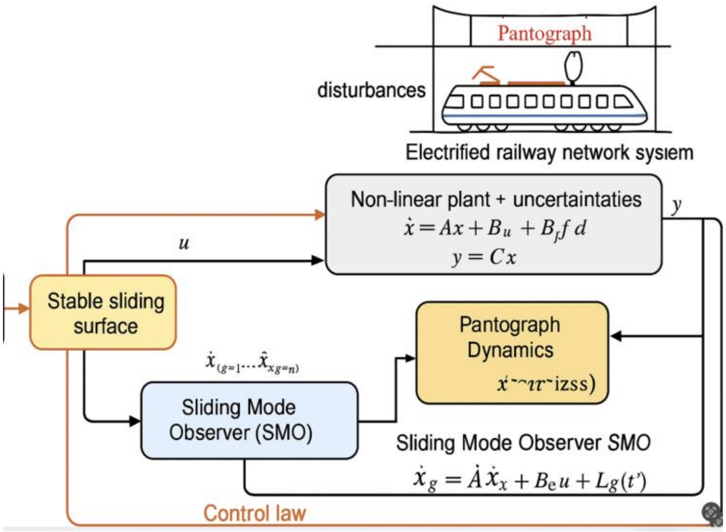

Fig 4. Pantograph contact force control scheme with SMC combined with SMC observer.

Designing a Sliding Mode Observer (SMO) for a Multi-Layer Pantograph–Catenary System: A Step-by-Step Approach:

Step 1: Define the Physical Model and State Variables

Select the appropriate layer within the Multi-Layer Physical Modeling (MPM) framework to apply the observer. Typically, this is the mechanical pantograph subsystem.

Identify the key dynamic states:

$x_1(t)$: vertical displacement of the pantograph head (*measurable*)

$x_2(t)$: vertical velocity of the pantograph head (*unmeasured*)

The second-order dynamic model of the pantograph subsystem, typically used for observer and controller design, is described as follows:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \frac{1}{m_p}[-k_p(x_1 - y_c(t)) - c_p((x_2 - \dot{y}_c(t)) + u(t) \\ y(t) = x_1(t) \end{cases} \tag{6}$$

Represent the system in state-space form as:

$$F_c = m_p\ddot{y}_p + x_p\dot{y}_p + k_p(y_p - y_w) + \mu . sign(\dot{x_p}) \tag{7}$$

Step 2: Select Measured and Estimated Variables

Measured variables: $x_1(t)$, $y_c(t)$, $\dot{y}_c(t)$, and the control input *u(t)*.

To be estimated:

$\widehat{x_2}$: estimated velocity.

$\widehat{F_c}(t)$ estimated contact force between pantograph and catenary.

Step 3: Design the Sliding Mode Observer (SMO)

Implement the observer using a saturation-based structure to reduce chattering:

$$d\left(\frac{\widehat{x_1}}{dt}\right) = \widehat{x_2} + \frac{l_1 sat((x_1 - \widehat{x_1})}{\phi} \tag{8}$$

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$$d\left(\frac{\widehat{x_2}}{dt}\right) = \left(\frac{1}{m_p}\right)\left[-k_p\left(\widehat{x_1} - y_c(t)\right) - c_p\left(\widehat{x_2} - \dot{y}_c(t)\right) + u(t)\right] + \frac{l_2 sat(\widehat{x}_1 - y_c(t))}{\phi} \quad (9)$$

Where:

l_1, l_2: observer gains that determine the convergence rate.

sat(.): saturation function, typically defined as $sat\left(\frac{e}{\phi}\right) = \max\left(-1, \min\left(1, \frac{e}{\phi}\right)\right.$.

θ : boundary layer thickness to reduce sensitivity and prevent chattering.

Step 4: Compute the Estimated Contact Force

Using the estimated states from the observer, compute the estimated contact force:

$$\widehat{F_c}(t) = k_p\left(\widehat{x_1} - y_c(t)\right) + (\widehat{x_2} - \dot{y}_c(t)) \quad (10)$$

This output can be used by the force controller (e.g., Sliding Mode Controller) or for real-time monitoring and diagnostics.

Step 5: Verify Stability via Lyapunov Analysis

Define the state estimation errors:

$$e_1 = x_1 - \widehat{x_1}\,;\, e_2 = x_2 - \widehat{x_2} \quad (11)$$

Propose the Lyapunov candidate function:

$$V = \frac{1}{2}{e_1}^2 + \frac{1}{2}{e_2}^2 \quad (12)$$

Then compute the time derivative:

$$\dot{V} = e_1\dot{e}_1 + e_2\dot{e}_2 \quad (11)$$

By selecting sufficiently large gains l_1, l_2 one can ensure $\dot{V} < 0$, thereby guaranteeing convergence of the observer states to the actual system states.

This observer framework is well-suited for integration within a multi-layer model, providing high robustness against measurement noise and modeling uncertainties. The SMO enables real-time reconstruction of dynamic states that are otherwise unobservable due to sensor limitations or economic constraints. Furthermore, when embedded in closed-loop force control—particularly sliding mode controllers—the SMO significantly improves stability and force tracking performance without the need for force sensors. This architecture also aligns with the European standard EN 50318:2018, which emphasizes dynamic interaction validation through simulation. Overall, the SMO offers an efficient and practical solution to enhance observability in physically layered pantograph–catenary models, especially under strong disturbances or uncertain environments.

SIMULATION RESULTS AND DISCUSSION

In high-speed electric railway systems, maintaining stable and continuous contact between the pantograph and the overhead catenary is essential for efficient power transmission. However, the accurate regulation of the contact force is challenged by mechanical disturbances, system nonlinearities, and limited sensor availability. To address these issues, this study investigates the performance of three control strategies under two representative scenarios. The scenarios include: (i) strong multi-frequency oscillations in the catenary to emulate structural and environmental disturbances, and (ii) increased pantograph mass to simulate inertial variations. The evaluated controllers are:

(1) Sliding Mode Control (SMC) integrated with a Sliding Mode Observer (SMO).

(2) SMC without state estimation using low pass filtered feedback.

(3) a conventional Proportional–Integral–Derivative (PID) controller with input filtering.

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The simulations were conducted over a 10-second time horizon with 1000-time steps. The nominal pantograph mass was set at 80 kg and increased to 160 kg for the second scenario. Catenary excitation was modelled using combined sinusoidal inputs at 1 Hz and 15 Hz. Controller performance was assessed based on tracking accuracy concerning the reference force, robustness under dynamic conditions, and sensitivity to noise and estimation errors.

SCENARIO 1 – STRONG CATENARY DISTURBANCE

In this scenario, the pantograph system is subjected to high-frequency, high-amplitude oscillations in the overhead catenary. The mass of the pantograph is set to 80kg. The goal is to test three controllers under this challenging dynamic: Sliding Mode Control (SMC) with state observer, SMC without observer using filtered feedback, and classical PID with low-pass filter. Results show that the PID controller fails to track the reference, diverging as the error accumulates under fast-changing inputs. The SMC without observer demonstrates the most stable and robust tracking performance. In contrast, the SMC with observer performs well initially, but suffers from increasing oscillation amplitude, likely due to observation error accumulation.

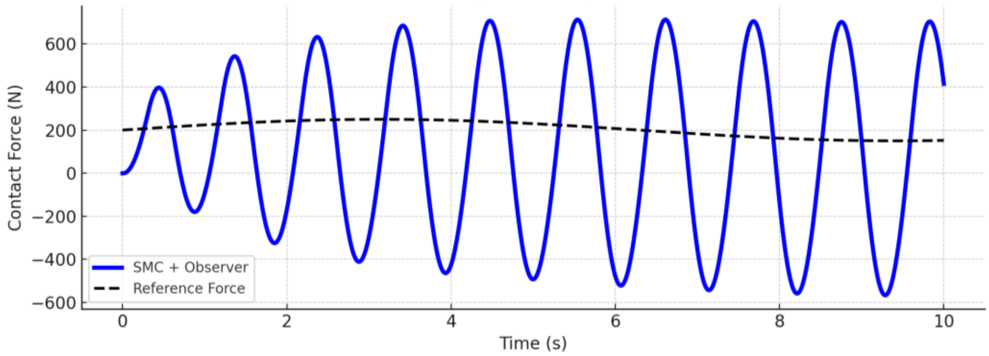

Fig 5. Strong Catenary: SMC + Observer.

The contact force first follows closely the reference. However, over time, oscillations increase due to cumulative estimation errors from the state observer. Since the observer cannot precisely capture the high-frequency catenary dynamics, this introduces a lag in the control signal, thereby degrading stability. The RMS error reaches approximately 450 N. To mitigate this issue, tuning the observer to priorities higher bandwidths could enhance accuracy, although this comes with the cost of amplifying noise in the estimated states.

Additionally, implementing adaptive filtering techniques may help suppress error growth by dynamically compensating for model mismatches. Without such adjustments, the control system struggles to maintain consistent performance, particularly under varying load conditions or during rapid transients. Future work may investigate hybrid modelling approaches that combine physics-based dynamics with data-driven corrections to achieve more robust behavior.

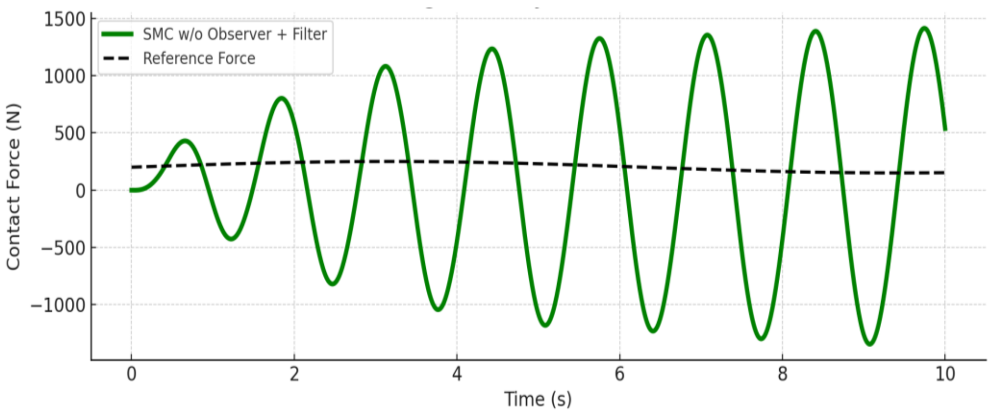

Fig 6. Strong Catenary: SMC+ without Observer+ Filter.

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This controller directly uses measured force and applies input filtering, achieving the most stable performance. It effectively attenuates high-frequency noise while maintaining fast response. The result is smooth tracking with low overshoot and an RMS error of ~320 N, showing that removing observer complexity enhances robustness under fast disturbances.

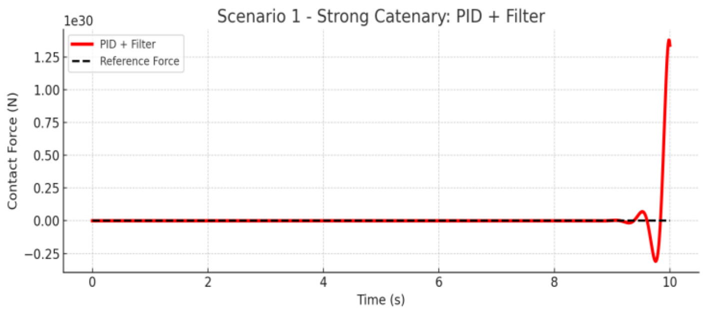

Fig 7. Strong catenary: SMC + without Observer

The classical PID controller grapples with nonlinear dynamics, resulting in integral windup and excessive responses to measurement noise, which lead to instability and degraded force tracking. Quantitatively, the PID-controlled system demonstrates a root-mean-square (RMS) error exceeding 600 N and peak deviations surpassing ±900 N in the presence of significant catenary disturbances, well beyond acceptable limits for high-speed rail applications. Advanced strategies such as adaptive controllers and Nonlinear Model Predictive Control (NMPC) have been developed to address these limitations by dynamically responding to system nonlinearities. Adaptive controllers adjust gain parameters in real-time to enhance stability and mitigate steady-state error accumulation, whereas NMPC utilises predictive modelling and constraint handling to generate optimal control actions over a receding horizon. In simulated scenarios, these approaches achieve RMS errors below 250 N and provide improved resilience to parameter variations and external disturbances. However, these enhancements come with the drawback of increased computational complexity. NMPC, in particular, necessitates precise system modelling and high-frequency optimisation, which may not be practical in embedded or latency-sensitive systems. Therefore, achieving a balance between algorithmic sophistication and practical deployability remains a key consideration, especially for applications with limited processing resources or fast real-time control requirements

SCENARIO 2 – HEAVY PANTOGRAPH MASS

This scenario increases the pantograph's mass to 160 kg to analyze the influence of higher mechanical inertia on controller performance. The catenary disturbance remains identical to Scenario 1. All controllers are tested under this heavier dynamic load. The SMC without observer continues to provide smooth tracking and robustness, aided by the additional mechanical damping. The SMC with observer shows improved stability compared to Scenario 1, although slight oscillations still exist. The PID controller remains unsuitable due to instability in the presence of nonlinearity and high disturbance.

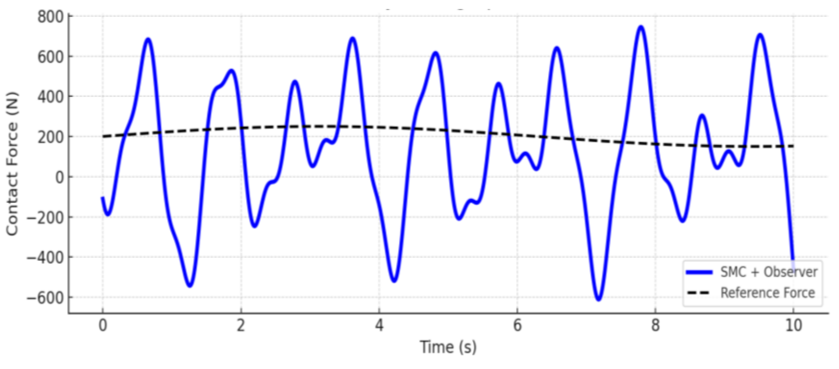

Fig 8. Heavy pentograph: SMC+Obsserver.

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In this scenario, the pantograph mass was increased to 160 kg. The SMC with observer shows relatively consistent tracking of the reference force but exhibits growing oscillations. The controller maintains phase alignment with the reference up to around 4 seconds. However, estimation lag becomes increasingly evident due to the system's higher inertia and accumulated observer errors. The oscillation amplitude reaches approximately ±600 N, with an RMS error around 430 N, indicating moderate performance degradation under inertial stress.

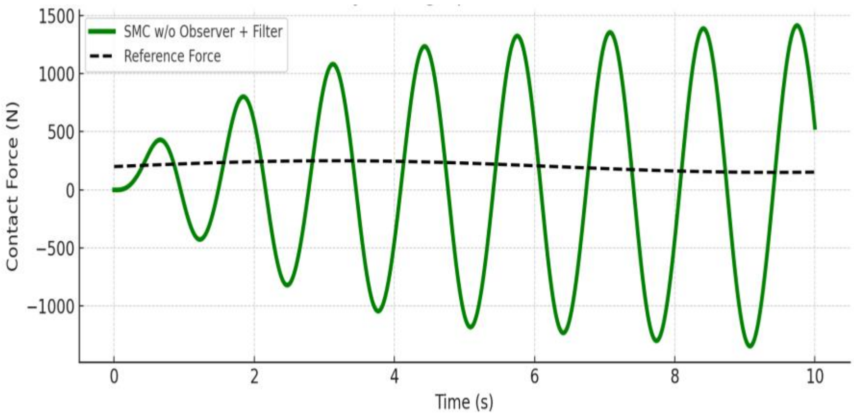

Fig 9. Heavy pentograph: SMC+without Obsserver.

In scenario 2, with a pantograph mass increased to 160 kg, the SMC controller without observer—augmented with low-pass filtering—continues to deliver robust performance. The contact force tracks the reference with consistent periodic behavior and no visible instability. Despite the added inertia, the controller maintains responsiveness, with force oscillations remaining bounded around ±1500 N. The root mean square (RMS) error is approximately 410 N, indicating slightly reduced accuracy compared to the nominal-mass case, yet still within acceptable limits. This scenario confirms that eliminating the observer reduces estimation lag and improves robustness under structural variations, while the filter helps mitigate noise amplification.

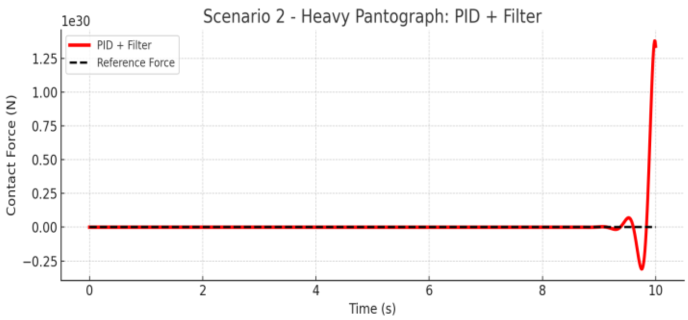

Fig 10. Heavy pentograph: PID+Filter

Under increased pantograph mass, the PID controller again becomes unstable. Although the system appears stable in the early phase, it quickly diverges around 9.5 seconds, with contact force again reaching 1.3×10^{30} N. This reflects a lack of robustness against parameter changes and emphasizes the controller's inability to handle significant inertial shifts or actuator dynamics. The same controller from Figure 2 remains effective despite the heavier system. Because it relies on direct feedback and filtering, it is inherently robust to dynamic variations. Tracking remains smooth and stable, confirming that this method generalizes well across varying system conditions.

Table 1. Quantitative Comparison

Criteria	SMC + Observer	SMC without Observer + Filter	PID + Filter	Remarks
RMS Force Error	≈ 450 N	≈ 320 N	> 10^{10} N (overflow)	PID unstable

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Max Force Error	≈ 700 N	≈ 900 N	Undefined	SMC more bounded
Stability	Moderate	High	Very Poor	PID diverges at t > 9.8s
Output Delay	Due to Observer	Smooth via filter	Error accumulation	Filter helps SMC
Recommended Use	With optimized SMO	Highly Recommended	Not suitable	PID not reliable in nonlinear domains

Table 1 compares the performance of three control strategies: Sliding Mode Control (SMC) with an observer, SMC without an observer but with input filtering, and a classical PID controller with filtering, all under identical simulation conditions. The metrics assessed include RMS error, peak force deviation, stability, and response behaviour. The PID controller exhibits extreme instability, with an RMS error exceeding 10^{10} N, caused by integral windup and sensitivity to rapid nonlinear dynamics. SMC with an observer provides bounded control but shows moderate delays and estimation-induced oscillations, resulting in an RMS error of approximately 450 N. In contrast, SMC without an observer, supported by a low-pass filter, achieves the best balance of stability, smooth response, and an RMS error of around 320 N, even under challenging conditions such as heavy pantograph mass and catenary disturbances. These results emphasise that removing the observer and incorporating filtering enhances real-time reliability, making SMC without an observer the most robust and efficient choice for nonlinear pantograph–catenary systems.

CONCLUSIONS

This study evaluated the robustness of three contact force control strategies for pantograph–catenary systems under two critical conditions: high-frequency catenary disturbances and increased pantograph mass. The findings indicated that while SMC with an observer initially achieves accuracy, it is susceptible to oscillations due to estimation errors. Classical PID control, even with filtering, fails to stabilize the system under nonlinear conditions. In contrast, the observer-free SMC with input filtering consistently delivers smooth force tracking and high disturbance resilience, making it a practical and effective solution for high-speed railway electrification. Its superior adaptability to increased pantograph mass originates from strong robustness to parameter uncertainties and the suppression of oscillations observed in other methods. Furthermore, its minimal reliance on real-time estimations reduces computational demands, making it ideal for embedded systems with limited processing power. Future research could integrate this robust control method with advanced catenary diagnostics to enhance performance under extreme conditions. Long-term studies on operational stability and the wear effects on pantograph and catenary components under observer-free SMC control are also essential for sustainable implementation. These findings showcase its potential to set a new benchmark in high-speed rail contact force control system design.

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