Proceedings of the Sixth International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 7, Paper 4.8
Civil-Comp Press, Edinburgh, United Kingdom, 2024
ISSN: 2753-3239, doi: 10.4203/ccc.7.4.8

A Robust Contact Force Estimation Method in Pantograph-Catenary System

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Abstract

In the realm of railway transportation, maintaining stable operation of pantograph systems for high-speed trains is crucial for ensuring passenger safety and system reliability. This study addresses the challenge of estimating contact force in pantograph systems, a key factor in maintaining stable operation. We proposed a simple but efficient method utilizing the Luenberger observer within a closed-loop system to estimate contact force based on measured accelerations. By conducting careful numerical analysis and computer simulations, we offered insights into the dynamic behavior of pantograph systems under varying operational conditions. Our results demonstrated the efficacy of the proposed algorithm in accurately estimating contact force, even under different train speeds and system uncertainties. Specifically, our analysis revealed that the algorithm could significantly estimate contact force across a range of train speeds, with only minor degradation observed at higher speeds. Furthermore, our investigation into system uncertainties highlighted the robustness of the algorithm, showing no significant degradation in performance up to 20% uncertainty in system parameters. By bridging theoretical modeling with practical application, this research contributed to advancing railway technology, ultimately enhancing operational efficiency and system reliability in high-speed railway networks.

Keywords: pantograph-catenary system, contact force, Luenberger observer design, fast analytical simulation, estimation, particle swarm optimization.

1 Introduction

Railway transportation has evolved significantly, embracing technological advancements to enhance passenger comfort, environmental sustainability, and operational efficiency. Central to this evolution are innovations such as active suspension systems, low-noise pantographs, and high-capacity drive systems, which have reshaped modern railway infrastructure. However, amidst these strides, ensuring the stability of current collection systems for high-speed operations remains a paramount concern [1]. At the core of this concern lies the stability of the power supply, reliant on consistent contact between pantographs and overhead power lines, particularly crucial for high-speed train operations [2]. Yet, maintaining stable operation proves challenging due to the dynamic interaction between the pantograph and overhead wire, influenced by factors such as variability in contact force [3].

Traditional approaches to pantograph system development have relied heavily on large-scale experimental facilities, albeit at considerable cost and time expense. Consequently, there is a demand for combined application of numerical analysis and data-driven approaches that are able to combine the results of computer model simulations to reduce the required computational resources to facilitate generation of the replication model [4,5]. A variety of techniques, including LiDAR, 3D and 6D models, FEM, and FEA, multi-physics modeling, and simulation methods, have emerged, facilitating the development of digital twins of railway infrastructures. These digital twins serve as virtual replicas of physical systems, offering insights into behavior and performance [4, 6–10]. However, ensuring the accuracy and reliability of these digital twins remains a challenge. Inaccuracies in predicting the behavior of pantograph-catenary systems can lead to operational inefficiencies and safety risks. Previous studies have focused on various aspects of this challenge, including the estimation of contact force between the pantograph and catenary, the development of observer models for system behavior estimation, and the application of physics-based models to simulate system interaction [4].

In the development studies of the active pantograph model, various observer models have been employed to account for the dynamic behavior of the pantograph. Considering the intricacies of the problem, a spectrum of observers has been utilized, including linear observers [11], non-linear observers such as Kalman-like [12] and Kalman observers [13], to characterize the system's behavior. In instances involving the utilization of more complex observer models, simplification becomes necessary. Notably, the model discussed in [13] introduces two additional state variables and an extra stiffness parameter, enriching the dynamic representation of the pantograph-catenary interaction. This variation underscores the significance of model selection tailored to the pantograph-catenary system's analytical requirements.

While these studies have made significant contributions, there remain gaps in addressing the complexities of real-world railway systems. One major question is regarding the impact of pantograph parameter variation and the resulting uncertainty on the observer performance. Another major question is the impact of train speed that can change the behavior of contact forces towards higher frequencies [14]. As a result, the practical application of advanced technologies such as active pantographs is hindered by theoretical complexities and high costs. In response to these challenges, this study proposes a simple but efficient method for estimating contact force, crucial for ensuring system stability. Leveraging the Luenberger observer within a closed-loop observer system, contact force estimation is facilitated based on measured accelerations of the pantograph system. By optimizing the design of the feedback observer through Particle Swarm Optimization (PSO) [15], we aim to minimize the disparity between actual and estimated contact forces, thereby enhancing system performance. In the subsequent sections, we delve deeper into our proposed method, offering insights into its implementation and performance evaluation. We analyze the pantograph system's behavior under varying travel speeds, aiming to bridge the gap between theoretical modeling and practical application. Readers can expect a detailed examination of the observation-oriented pantograph model and robust contact force estimation method, followed by numerical results and discussions highlighting the efficiency of our approach.

2 Observation oriented pantograph model

Researchers extensively explore pantograph models to understand their behavior under varying operational conditions. Finite Element Methods (FEM) are commonly used for analyzing pantograph-catenary systems under static conditions, providing precise insights into their structural responses [8]. However, FEM algorithms face challenges in dynamic assessments due to their computational demands, limiting their applicability for real-time applications. Lumped mass-spring-damper models offer advantages in analyzing the dynamic behavior of pantograph systems.
Despite the outcomes observed with two-degree-of-freedom models in simulating pantograph dynamic behavior, this study employs a three-degree-of-freedom model. A three-degree-of-freedom lumped mass-spring-damper model serves as a suitable dynamic representation, capturing the intricate interaction among pantograph components and the overhead catenary wire. As depicted in Figure 1, the masses, denoted as m_1, m_2, and m_3, correspond to upper and lower arm components, collector head guidance component, collector component, and contact piece, respectively. These masses are interconnected through a combination of parallel damper and spring mechanisms. Notably, m_3 maintains direct contact with the contact wire, with all applied contact forces on the pantograph represented by $P(t)$.
To derive the dynamical model of the system, the free-body diagram of each mass is evaluated using Newton's second law. This leads to a system of differential equations governing the motion of each component as follows:

$$\begin{aligned} m_1\ddot{y_1} &= -(k_1 + k2)y_1 - (c_1 + c_2)\dot{y_1} + k_2y_2 + c_2\dot{y_2} \\ m_2\ddot{y_2} &= -(k_2 + k_3)y_2 - (c_2 + c_3)\dot{y_2} + k_2y_1 + c_2\dot{y_1} + k_3y_3 + c_3\dot{y_3} \\ m_3\ddot{y_3} &= P(t) - k_3y_3 - c_3\dot{y_3} + k_3y_2 + c_3\dot{y_2} \end{aligned} \tag{1}$$

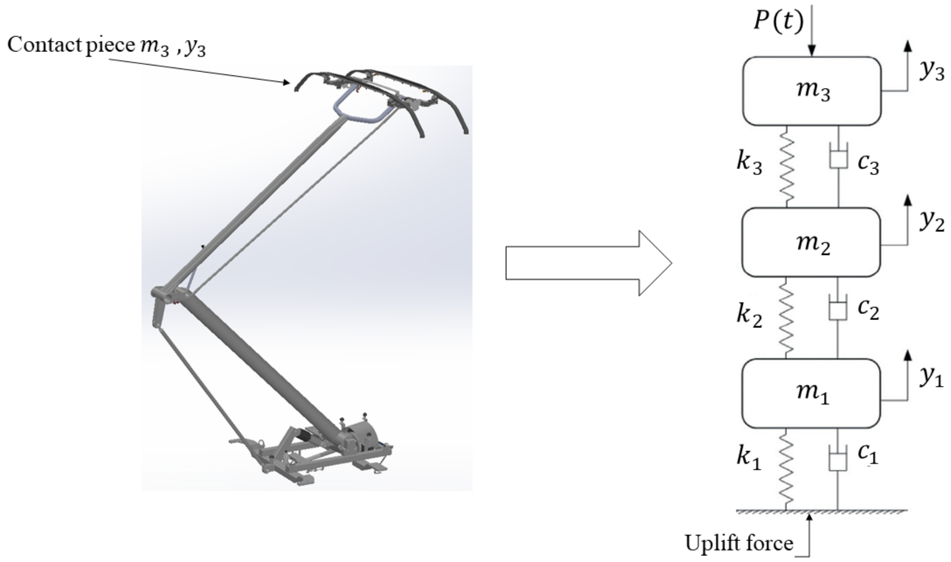

Figure 1: Dynamic modeling of the pantograph. The interaction between pantograph components are represented through spring and damper elements.

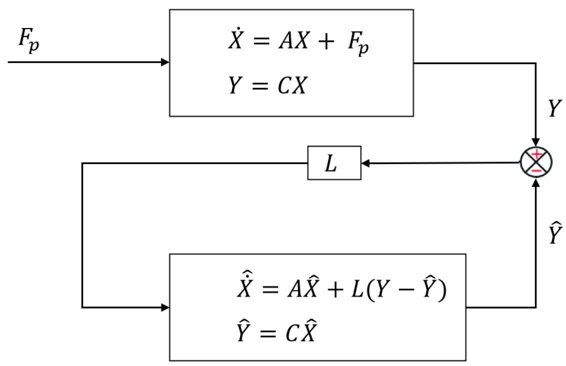

Figure 2: Estimation of state variables using Luenberger observer, utilized to calculate the estimated contact force $\hat{P}(t)$.

where uplift force is considered as zero for ease of calculation. Therefore, the state space representation of the system can be derived by defining the state vector as $X = [x_1, x_2, x_3, x_4, x_5, x_6]^T = [y_1, y_2, y_3, \dot{y_1}, \dot{y_2}, \dot{y_3}]^T$, and the output vector $Y = [\ddot{y_2}, \ddot{y_3}]$ as the measured acceleration of masses m_2 and m_3, respectively. Consequently, the state space representation of the passive pantograph system is obtained, allowing for the analysis of its dynamic behavior as follows:

$$\begin{aligned} \dot{X} &= AX + F_p \\ Y &= CX \end{aligned} \tag{2}$$

where the state space matrices A and C, and the input disturbance F_p are represented as follows:

$$\mathbf{A} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ \frac{-(k_1+k_2)}{m_1} & \frac{k_2}{m_1} & 0 & \frac{-(c_1+c_2)}{m_1} & \frac{c_2}{m_1} & 0 \\ \frac{k_2}{m_2} & \frac{-(k_2+k_3)}{m_2} & \frac{k_3}{m_2} & \frac{c_2}{m_2} & \frac{-(c_2+c_3)}{m_2} & \frac{c_3}{m_2} \\ 0 & \frac{k_3}{m_3} & \frac{-k_3}{m_3} & 0 & \frac{c_3}{m_3} & \frac{-c_3}{m_3} \end{bmatrix}, \mathbf{F_p} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \frac{P(t)}{m_3} \end{bmatrix} \tag{3}$$

$$\mathbf{C} = \begin{bmatrix} \frac{k_2}{m_2} & \frac{-(k_2+k_3)}{m_2} & \frac{k_3}{m_2} & \frac{c_2}{m_2} & \frac{-(c_2+c_3)}{m_2} & \frac{c_3}{m_2} \\ 0 & \frac{k_3}{m_3} & \frac{-k_3}{m_3} & 0 & \frac{c_3}{m_3} & \frac{-c_3}{m_3} \end{bmatrix}$$

3 Robust contact force estimation method

This section delves into the proposed method for estimating the contact force $P(t)$. The objective is to compute the estimated contact force $\hat{P}(t)$ based on the measurements of output accelerations $Y = [\ddot{y_2}, \ddot{y_3}]$. The estimation process of contact force is outlined as follows:

$$\hat{P}(t) = m_3\ddot{y_3} + k_3\hat{y}_3 + c_3\hat{\dot{y}}_3 - k_3\hat{y}_2 - c_3\hat{\dot{y}}_2 \tag{4}$$

In this context, $\hat{y}_3$, $\hat{\dot{y}}_3$, $\hat{y}_2$, and $\hat{\dot{y}}_2$ are estimated using an observation mechanism. The Luenberger observer was chosen for its simplicity and proven efficacy in the literature [16]. The closed-loop observer system, depicted in Figure 2, is utilized to estimate the states of the pantograph system, facilitating the calculation of $\hat{P}(t)$ as defined in equation (4). It's crucial to emphasize that the primary objective of employing observer L is not to observe the states of the system but rather to estimate the contact force $P(t)$. Therefore, the task requires designing a feedback observer aimed at minimizing the disparity between $P(t)$ and $\hat{P}(t)$. To accomplish this, one can find the poles λ of the closed-loop observer system by formulating the optimization problem as follows:

$$\begin{aligned} &\min_{\lambda} \|P(t) - \hat{P}(t)\| \\ &\quad subject\ to \\ &\quad \dot{X} = AX + F_p \\ &\quad Y = CX \\ &\quad \dot{\hat{X}} = A\hat{X} + L(Y - \hat{Y}) \\ &\quad \hat{Y} = C\hat{X} \\ &\quad \Re(\lambda) < 0 \end{aligned} \tag{5}$$

where, the poles λ are selected to minimize the disparity between $P(t)$ and $\hat{P}(t)$, and the inequality $\Re(\lambda) < 0$ necessitates that the poles of the closed-loop observer system remains stable. In this setup, the feedback observer L is selected to ensure that the

Parameters	Symbol	Value
Mass of frame	m_1	7.5kg
Mass of collector piece	m_2	9kg
Mass of contact piece	m_3	6kg
Stiffness of frame	k_1	7000N/m
Stiffness of collector piece	k_2	15500N/m
Stiffness of contact piece	k_3	160N/m
Damping of frame	c_1	45N.m/s
Damping of collector piece	c_2	0.1N.m/s
Damping of contact piece	c_3	100N.m/s

Table 1: Parameters of the 3-DoF pantograph model

eigenvalues of the closed-loop observer system $A^T - C^T L$ align with the desired poles λ. To achieve this, Particle Swarm Optimization (PSO) [15] is employed to select the eigenvalues of the observer system A_L, through minimizing the optimization problem (5).

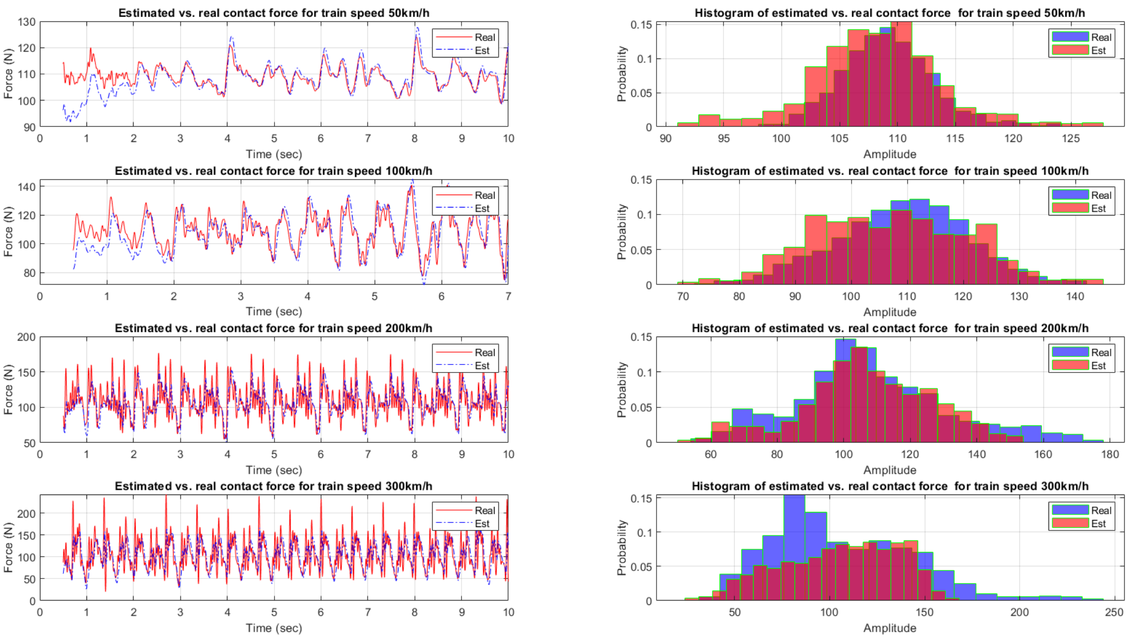

Figure 3: (left) Estimated force using Luenberger observer under different train speed up to 300km/h. (right) The histogram of the simulated contact force $P(t)$ and its estimation $\hat{P}(t)$.

Force	**Min**	**Max**	**Mean**	**StD**	**Kur**
P_{50}	97.2	121.1	109.2	3.9	3.7
$\hat{P}_{50}$	91.1	125.0	108.1	5.6	4.0
P_{100}	73.4	146.8	110.1	12.2	2.7
$\hat{P}_{100}$	65.4	151.5	108.5	14.3	2.4
P_{200}	38.1	178.0	108.1	23.3	3.0
$\hat{P}_{200}$	47.6	166.1	106.8	19.7	2.9
P_{300}	-6.2	**218.8**	106.3	37.5	3.2
$\hat{P}_{300}$	13.7	**196.5**	105.1	30.4	2.1

Table 2: Contact force signal features under different train speed

4 Numerical results

In this section, closed-loop simulations are employed to assess the performance of the framework within the context of contact force estimation in pantograph-catenary systems. The simulation parameters of the real system are adjusted with respect to Table 1, which is often relatable to the parameters of pantographs used in electric locomotives. Specifically, the framework's efficacy is evaluated in force estimation for high-speed train operation under system uncertainty. For this matter, we utilized the simulation software developed in [10] to generate precise contact forces applied from catenary to pantograph $P(t)$. In contrast to FEM models, an analytical model was employed to simulate the dynamic behavior of the catenary [10]. After examining a combination of fast analytical approach for modeling catenary combined with lumped-mass-spring-damper applied to predict the behaviour of the system, it becomes apparent that the employed model is the right model choice, essential for accurate behaviour prediction.

In the first step, the estimation of contact force under different train speeds has been checked under the assumption of the known system parameters according to Table 1. Further, for each signal, all its statistical parameters, including mean μ, standard deviation σ, kurtosis, statistical minimum defined as $\mu - 3\sigma$, and statistical maximum as $\mu + 3\sigma$ [17], have been compared between contact force signal and its estimation. Then, the sensitivity analysis of model robustness investigated for the worst-case scenario of high-speed train, with the assumption of different uncertainties in the main of the system parameters, it has been shown that the performance of the observer system would not degrade significantly up to 20% uncertainty. The detailed analysis of both scenarios is given in the following section. This result is fully aligned with the real system behavior due to the expected failure in dropper buckling.

4.1 Force Estimation under Different Train Speed

A major question regarding the efficiency of the observer is if it can maintain its performance under different operating conditions, and to what extent different conditions can degrade its performance. Among these operating conditions, the train speed has the most impact on contact forces. As the train speed increases, more impacts will show up in the contact force signal due to the dropper buckling, and more amplitudes will be expected. To evaluate this matter, we generated different contact forces through a high-precision fast analytical approach [10]. Then, for each corresponding contact force, the Luenberger observer was utilized to calculate the estimated contact force $\hat{P}$. As illustrated in Figure 3, both the contact force and its estimation for four different train speeds including 50 km/h, 100 km/h, 200 km/h, and 300 km/h, from easy conditions to the most difficult one, showed that the proposed algorithm can significantly estimate the contact force. However, there was a slight degradation in the histogram of the 300 km/h train speed, indicating that the estimated contact force has some problem with the peak of the signal. This issue is highlighted in Table 2, showing a 22.3N difference between the statistical maximum of signals.

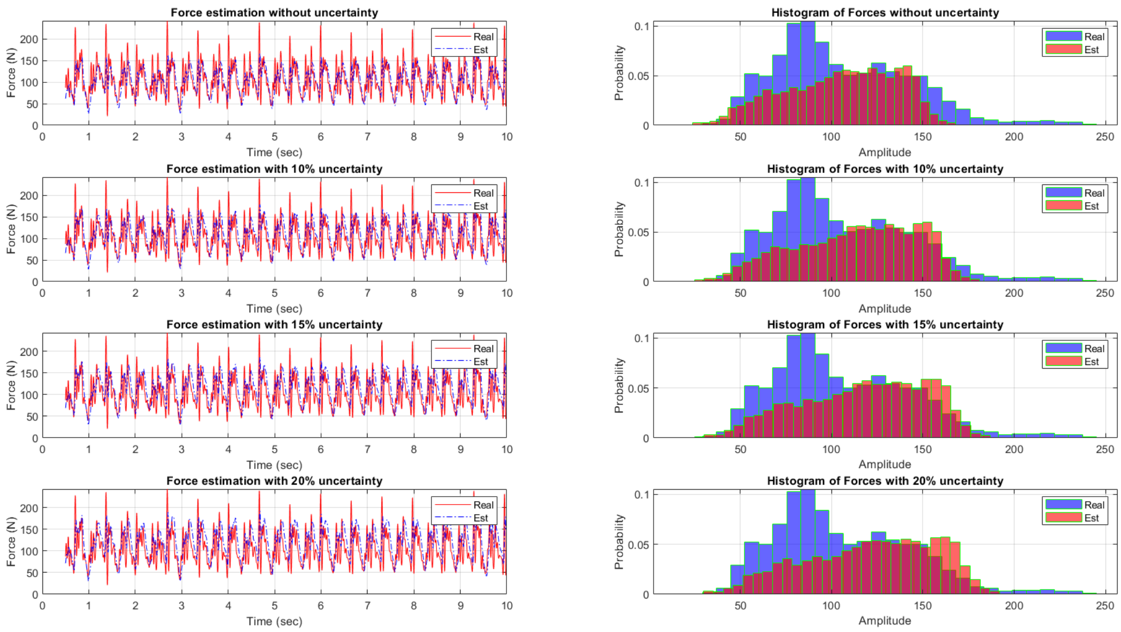

Figure 4: (left) Estimated force using Luenberger observer under different parameter's uncertainty up to 20%. (right) The histogram of the real contact force $P(t)$ and its estimation $\hat{P}(t)$

Force	**Min**	**Max**	**Mean**	**StD**	**Kur**
P	-6.2	218.8	106.3	37.5	3.2
$\hat{P}$	13.7	196.5	105.1	30.4	2.1
$\hat{P}_{10\%}$	14.8	211.6	113.2	32.8	2.1
$\hat{P}_{15\%}$	15.3	219.2	117.3	33.9	2.1
$\hat{P}_{20\%}$	15.8	226.8	121.3	35.1	2.1

Table 3: Contact force signal features under different system parameter's uncertainty

4.2 Force Estimation under Different System Uncertainties

We further analyzed the performance of the observer under different uncertainties in system parameters, including all masses, dampings, and spring stiffness. For this end, we examined the contact force of a train with a speed of 300 km/h, which represents the worst-case scenario. As a result of added uncertainty to the system parameters, the observer would have access to the estimation of system matrices $\hat{A}$ and $\hat{C}$, which will be used for estimation. Four different uncertainties including No uncertainty, 10%, 15%, and 20% uncertainties were considered as depicted in Figure 4. As illustrated in the histogram figures, both the estimated and real contact forces exhibit high probability around their respective mean values, indicating precise estimation capability for the observer. Also, the histograms show no meaningful changes in the performance of the observer system, with a slight degradation of the mean value in $\hat{P}_{20\%}$ (See Table 3). The overall performance of the observer system shows a meaningful 14% mean error in the worst scenario under the worst uncertainty.

5 Conclusion

In this study, we proposed a simple but efficient method for estimating contact force in pantograph systems, crucial for maintaining stable operation in high-speed railway networks. Leveraging the Luenberger observer within a closed-loop observer system, we facilitated contact force estimation based on measured accelerations. Our investigation revealed that the proposed algorithm can significantly estimate contact force under different train speeds, with a slight degradation observed at higher speeds. Furthermore, our analysis demonstrated that the observer system's performance remains robust even under different uncertainties in system parameters, highlighting its reliability in practical applications. This research contributes to the advancement of railway technology, paving the way for enhanced operational efficiency and system reliability in high-speed railway networks. Future research could focus on further refining the proposed method, selection of more precise and complex pantograph models, and conducting real-world experiments to validate its effectiveness. In conclusion, our study underscores the importance of accurate contact force estimation in ensuring the stability and safety of high-speed railway operations, ultimately contributing to the development of more efficient and reliable railway systems.

Acknowledgement

This work was supported and funded by PANTOhealth GmbH. We extend special thanks to Dr. Vahid Bokaeian for his invaluable review of this paper and his scientific insights.

References

[1] Han F, Liu Z, Wang C. Research on a comfort evaluation model for high-speed trains based on variable weight theory. Applied Sciences. 2023 Feb 28;13(5):3144.

[2] Wu G, Dong K, Xu Z, Xiao S, Wei W, Chen H, Li J, Huang Z, Li J, Gao G, Kang G. Pantograph–catenary electrical contact system of high-speed railways: recent progress, challenges, and outlooks. Railway Engineering Science. 2022 Dec;30(4):437-67.

[3] Anastasio D, Marchesiello S, Garibaldi L, Claudio S, Alessio I. Improvements of the pantograph-catenary interaction: numerical simulations and experimental tests on the Italian high-speed overhead contact line. InProceedings of The Fifth International Conference on Railway Technology: Research, Development and Maintenance 2022 (Vol. 1, pp. 1-8). Computational & Technology Resources.

[4] Ghaboura S, Ferdousi R, Laamarti F, Yang C, El Saddik A. Digital Twin for Railway: A Comprehensive Survey. IEEE Access. 2023 Oct 23;11:120237-57.

[5] De Donato L, Dirnfeld R, Somma A, De Benedictis A, Flammini F, Marrone S, Saman Azari M, Vittorini V. Towards AI-assisted digital twins for smart railways: preliminary guideline and reference architecture. Journal of Reliable Intelligent Environments. 2023 Sep;9(3):303-17.

[6] Wang H, Liu Z, Núñez A, Dollevoet R. Identification of the catenary structure wavelength using pantograph head acceleration measurements. In2017 IEEE International Instrumentation and Measurement Technology Conference (I2MTC) 2017 May 22 (pp. 1-6). IEEE.

[7] Song Y, Wang H, Frøseth G, Nåvik P, Liu Z, Rønnquist A. Surrogate modelling of railway pantograph-catenary interaction using deep Long-Short-Term-Memory neural networks. Mechanism and Machine Theory. 2023 Sep 1;187:105386.

[8] Wang H, Song Y, Wang X, Liu Z. Fenet: A Deep Learning Model for Finite Element Dynamics Simulation and its Application in Pantograph-Catenary System. Available at SSRN 4623634.

[9] Wu M, Xu X, Zhang H, Zhou R, Wang J. Pantograph–Catenary Interaction Prediction Model Based on SCSA-RBF Network. Applied Sciences. 2024 Jan 4;14(1):449.

[10] Vesali F, Rezvani MA, Molatefi H. Simulation of the dynamic interaction of rail vehicle pantograph and catenary through a modal approach. Archive of Applied Mechanics. 2020 Jul;90(7):1475-96.

[11] Vesali F, Molatefi H, Rezvani MA, Moaveni B, Hecht M. New control approaches to improve contact quality in the conventional spans and overlap section in a high-speed catenary system. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. 2019 Oct;233(9):988-99.

[12] Chater E, Ghani D, Giri F, Haloua M. Output feedback control of pantograph–catenary system with adaptive estimation of catenary parameters. Journal of Modern Transportation. 2015 Dec;23:252-61.

[13] Ide CK, Olaru S, Rodriguez-Ayerbe P, Rachid A. A nonlinear state feedback control approach for a Pantograph-Catenary system. In2013 17th International Conference on System Theory, Control and Computing (ICSTCC) 2013 Oct 11 (pp. 268-273). IEEE.

[14] Schick B, Liu Z, Stichel S. Modelling of pantograph-catenary interaction around critical speed. InThe Fifth International Conference on Railway Technology: Research, Development and Maintenance 22-25 August, 2022— Montpellier, France 2022.

[15] Kennedy J, Eberhart R. Particle swarm optimization. In Proceedings of ICNN'95-international conference on neural networks 1995 Nov 27 (Vol. 4, pp. 1942-1948). ieee.

[16] Luenberger D. An introduction to observers. IEEE Transactions on automatic control. 1971 Dec;16(6):596-602.

[17] EN 50317:2012, The European Standard, Railway applications - Current collection systems - Requirements for and validation of measurements of the dynamic interaction between pantograph and overhead contact line, 2012.