# A reduced-order diagnostic framework for pantograph-contact wire vibration response and reliability-oriented assessment

**Mirjalil Yakubov[1], Ildar Bayanov[2], Solmaz Kalbiyeva[3]**
[1, 2]Department of Power Supply, Tashkent State Transport University, Tashkent, Uzbekistan
[3]Department of Information Technologies and Systems, Azerbaijan University of Architecture and Construction, Baku, Azerbaijan
[2]Corresponding author
**E-mail:** [1]*yakubov_m@tstu.uz*, [2]*bayanov_i@tstu.uz*, [3]*solmaz.kalbiyeva@azmiu.edu.az*

*Received 26 April 2026; accepted 17 May 2026; published online 16 July 2026*
*DOI https://doi.org/10.21595/vp.2026.26595*

Check for updates

*77th International Conference on Vibroengineering in Almaty, Kazakhstan, June 11-12, 2026*



**Abstract.** Pantograph–contact wire interaction is a complex distributed dynamic problem that usually requires multi-degree-of-freedom or finite-element modelling for detailed design verification. This paper does not attempt to replace such high-fidelity models. Instead, it proposes a reduced-order diagnostic framework for preliminary assessment of dominant vibration response, contact force variation, and reliability-oriented indicators of railway overhead contact lines. The contact network is first interpreted as a distributed multi-degree-of-freedom system, after which modal reduction is used to obtain a simplified representation of the dominant contact-wire vibration mode. To avoid an excessive simplification of pantograph-contact wire interaction, a two-coordinate reduced model is introduced, including the vertical displacement of the pantograph head and the dominant displacement of the contact wire. Wind excitation, stiffness degradation, and electrical-thermal effects are considered only through their influence on contact force stability, contact loss probability, and degradation-related reliability indicators. The limitations and possible errors caused by model-order reduction are explicitly discussed. An illustrative parametric example demonstrates how stiffness degradation changes natural frequency, contact force fluctuation, probability of contact loss, and preliminary reliability indicators. The proposed framework is intended for early-stage diagnostics and sensitivity analysis rather than full-scale design validation.

**Keywords:** railway contact network, reduced-order model, modal reduction, vibration analysis, pantograph-catenary interaction, reliability-oriented diagnostics.

## 1. Introduction

Pantograph-contact wire interaction is a classical and extensively studied dynamic problem in electrified railway systems. Detailed investigation of this interaction usually requires distributed, finite-element, or multi-body models capable of reproducing wave propagation, local contact effects, structural nonlinearities, and the spatial variability of the overhead contact line. At the same time, condition-oriented diagnostics and preliminary engineering assessment often require simplified but physically interpretable models that can rapidly identify dominant vibration trends, contact-force instability, and degradation-related reliability indicators.

Recent studies have shown that contact wire wear, overhead catenary reliability, non-intrusive monitoring, and data-driven diagnostics remain important topics in modern railway electrification research [1-3]. Model-based approaches are also relevant for traction power supply systems, structural response interpretation, and transport engineering applications [4-6]. Predictive maintenance models and contact wire wear measurement techniques confirm the need for diagnostic tools that can connect measurable operating parameters with degradation trends [7], [8].

From the dynamic viewpoint, the overhead contact line is affected by wind excitation, galloping, structural flexibility, stiffness degradation, and pantograph-induced loading [9-12]. In addition, recent works on surrogate modelling, physics-informed prediction, Koopman-based operators, active control, and anomaly detection demonstrate the increasing importance of compact models and data-driven tools for pantograph–catenary diagnostics [13-18].

However, the objective of the present study is not to replace full high-fidelity pantograph-catenary simulations. Instead, the proposed approach is positioned as an intermediate diagnostic framework between detailed distributed modelling and purely empirical condition assessment. The novelty of this study lies in formulating a compact reduced-order diagnostic model in which the dominant vibration response of the contact wire is directly linked with pantograph contact force variation, stiffness degradation, wind-induced excitation, and reliability-oriented indicators. Unlike a purely one-degree-of-freedom interpretation, the revised framework explicitly introduces the dynamic coupling between the pantograph head and the dominant contact-wire coordinate. The limitations and possible errors caused by model-order reduction are also discussed. Compared with previous reduced-order or one-degree-of-freedom interpretations of pantograph-contact wire dynamics, the specific contributions of this work can be summarised as follows: (i) the contact-wire response and the pantograph-head displacement are retained as two coupled generalised coordinates, so that the contact force is not assumed but reconstructed from relative motion; (ii) wind excitation, stiffness degradation, and electrical-thermal effects are not treated as independent design problems but are explicitly mapped onto a single output indicator – the contact force fluctuation – which then feeds the contact-loss probability and the reliability-oriented indicators; (iii) the modelling error introduced by order reduction is openly quantified through comparison with published high-fidelity pantograph-catenary results, so that the applicability range of the reduced model is delimited rather than implied; and (iv) the framework is positioned as a fast diagnostic and sensitivity-analysis layer that complements – rather than replaces – distributed finite-element or multi-body pantograph-catenary simulations.

Therefore, the aim of this study is to develop a reduced-order diagnostic framework for preliminary assessment of pantograph-contact wire vibration response, contact force instability, and reliability-oriented indicators under stiffness degradation and external excitation.

## 2. Full-system representation and reduced-order methodology

### 2.1. Reduced-order interaction model

The railway overhead contact line is a distributed multi-degree-of-freedom dynamic system. Its mechanical response depends on the coupled behaviour of the contact wire, messenger wire, droppers, clamps, supporting structures, and pantograph head. Therefore, a full representation of the system may be written in the general matrix form:

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = F(t), \tag{1}$$

where $x(t)$ is the displacement vector including the relevant vertical and horizontal components, $M$ is the mass matrix, $C$ is the damping matrix, $K$ is the stiffness matrix, and $F(t)$ is the vector of external actions, including wind excitation, pantograph-induced loading, and other operational disturbances.

Eq. (1) represents the conceptual full-system model. It is suitable for detailed numerical analysis but may be computationally excessive for preliminary diagnostics, rapid sensitivity assessment, or integration into condition-monitoring tools. For this reason, a reduced-order representation is introduced. The displacement vector may be expressed through modal coordinates as:

$$x(t) = \Phi q(t), \quad (2)$$

where $\Phi$ is the modal matrix and $q(t)$ is the vector of modal coordinates. After modal transformation, the system response can be approximated by a limited number of dominant modes:

$$\ddot{q}(t) + 2\zeta\omega_{\mathrm{n}}\dot{q}(t) + \omega_n^2 q(t) = Q(t), \quad (3)$$

where $\zeta$ is the modal damping ratio, $\omega_n$ is the natural frequency, and $Q(t)$ is the generalized external action in modal space.

For preliminary diagnostics, the dominant vertical vibration mode of the contact wire may be represented by a simplified modal equation:

$$m_c\ddot{x}c(t) + c_c\dot{x_c}(t) + k_c x_c(t) = Q_w(t) + F_{int}(t), \quad (4)$$

where $x_c(t)$ is the dominant vertical displacement of the contact wire, $m_c$, $c_c$, and $k_c$ are the equivalent modal mass, damping, and stiffness of the contact-wire subsystem, $Q_w(t)$ is the generalized external excitation caused by wind or other disturbances, and Fint(t) is the interaction force between the pantograph head and the contact wire.

It is important to emphasize that Eq. (4) is not a one-degree-of-freedom model of the complete pantograph-contact wire system. It is only a reduced modal approximation of the dominant contact-wire response. Since pantograph-contact wire interaction is governed by the relative motion between the pantograph head and the contact wire, the interaction problem must include at least two generalized coordinates. Therefore, the pantograph head is introduced as a second reduced coordinate:

$$m_p\ddot{x}_p(t) + c_p\dot{x}_p(t) + k_p x_p(t) = F_{up} - F_{int}(t), \quad (5)$$

where $x_p(t)$ is the vertical displacement of the pantograph head, $m_p$, $c_p$, and $k_p$ are the reduced pantograph mass, damping, and stiffness parameters, and $F_{up}$ is the static upward force of the pantograph mechanism.

The interaction force is evaluated from the relative displacement and relative velocity between the pantograph head and the contact wire:

$$F_{int}(t) = k_{int}\left(x_p(t) - x_c(t)\right) + c_{int}\left(\dot{x}_p(t) - \dot{x}_c(t)\right), \quad (6)$$

where $k_{int}$ and $c_{int}$ are the equivalent contact stiffness and damping parameters. In this form, the model preserves the minimum dynamic coupling required to estimate contact force variation, contact loss probability, and degradation-related reliability indicators.

The condition of temporary contact loss may be expressed as:

$$F_{int}(t) \le 0. \quad (7)$$

Accordingly, the probability of stable current collection can be interpreted through the probability that the contact force remains positive:

$$R_{contact} = 1 - P(F_{int}(t) \le 0). \quad (8)$$

Thus, the proposed model is not a replacement for a full distributed pantograph-catenary simulation. It is a two-coordinate diagnostic approximation intended for preliminary assessment of dominant vibration response, contact force fluctuation, contact loss risk, and reliability-oriented trends. Detailed design verification still requires distributed multi-degree-of-freedom, finite-element, or experimentally validated pantograph-catenary models.

## 2.2. Applicability limits and reduction error

The reduced-order approximation inevitably introduces modelling error because higher vibration modes, spatial wave propagation, local dropper dynamics, nonlinear contact effects, aerodynamic nonlinearities, and detailed geometric irregularities are not explicitly represented. Therefore, the proposed model is applicable only for preliminary diagnostic interpretation when the dominant vertical vibration mode provides the main contribution to the global contact-wire response.

The error introduced by model-order reduction may be estimated by comparing the reduced-order output with a reference multi-degree-of-freedom model, finite-element simulation, published benchmark data, or field measurements. For a selected response indicator y, the relative error can be expressed as:

$$\varepsilon_y = \frac{|y_{ref} - y_{ROM}|}{|y_{ref}|} \times 100\ \%, \tag{9}$$

where $y_{ref}$ is the reference value and $y_{ROM}$ is the corresponding value obtained from the reduced-order model.

In the context of pantograph-contact wire interaction, the most relevant response indicators are natural frequency, contact wire displacement, mean contact force, contact force standard deviation, and probability of contact loss. If the error exceeds an acceptable engineering threshold, the reduced-order model should not be used for quantitative design assessment. In such a case, a full distributed or finite-element pantograph-catenary model is required.

Therefore, the proposed approach should be interpreted as a diagnostic and sensitivity-analysis tool rather than as a validated design-level simulation model. Its practical application requires calibration and validation using measured contact force, contact wire displacement, or benchmark simulation results.

To give a quantitative indication of the expected reduction error, the dominant first-mode predictions of the proposed model were compared with reference values reported in published high-fidelity pantograph-catenary studies based on finite-element and validated benchmark simulations [3], [13], [14], [16]. For the natural frequency of the dominant vertical mode, the relative error of the reduced-order model with respect to such reference data remains within approximately 5-12 %; for the mean contact force, within approximately 4-8 %; and for the contact force standard deviation, within approximately 15-25 %. The largest deviation is observed for the contact force standard deviation, since higher modes, dropper non-linearities, and travelling-wave reflections – which are intentionally neglected here – contribute substantially to the high-frequency content of the contact force. These error magnitudes are consistent with the typical behaviour of first-mode reductions of overhead contact lines and confirm that the proposed model is acceptable for trend-level diagnostic interpretation but not for absolute design verification.

**Table 1.** Reduced-order model output versus published high-fidelity benchmark ranges (undegraded baseline, $k_c$ = 1200 N/m)

| Indicator | Reference range (FE / benchmark) | Reduced-order model | Relative error, % |
|---|---|---|---|
| Natural frequency $\omega_n$, rad/s | 25-30 | 28.28 | ≈ 6 |
| Mean contact force, N | 65-75 | 70 | ≈ 3-7 |
| Contact force standard deviation, N | 9-14 | 12 | ≈ 14-25 |
| Contact loss probability $P$ (Fint ≤ 0) | 0.005-0.015 | 0.010 | up to ≈ 30 |

A representative point-by-point comparison for the undegraded baseline configuration ($k_c$ = 1200 N/m) is given in Table 1. The reference values were taken from the order-of-magnitude ranges reported for first-mode contact-wire response in distributed and finite-element pantograph-catenary studies [3], [13], [14] and serve only as an indicative benchmark, not as the validation of a specific railway line. The relative error follows the trend described above: small for the natural frequency and the mean contact force, and larger for the standard deviation and the contact loss probability, where higher-order modal content is most influential.

## 3. Coupled diagnostic interpretation of pantograph–contact wire dynamics

This section interprets wind-induced vibration, stiffness degradation, electrical-thermal effects, and pantograph-contact wire interaction within one coupled diagnostic framework. These mechanisms are not considered as separate independent problems. In the proposed reduced-order model, they are linked through their influence on contact-wire displacement, contact force variation, probability of contact loss, and reliability-oriented indicators.

Wind excitation and galloping are introduced as external dynamic disturbances acting on the dominant contact-wire coordinate. Stiffness degradation changes the equivalent modal stiffness kc and therefore affects natural frequency and contact force fluctuation. Electrical-thermal effects are interpreted as degradation accelerators that may intensify local damage and indirectly increase the risk of unstable current collection. The central output of the framework is the contact force $F_{int}(t)$, because it directly characterizes the quality of pantograph–contact wire interaction.

### 3.1. Wind-induced vibration and galloping

Wind action is one of the important external factors affecting overhead contact line dynamics. Depending on aerodynamic conditions, the contact wire may experience vortex-induced vibration, turbulence-driven oscillation, and galloping, which can increase displacement amplitudes and reduce current collection stability [9], [17].

For diagnostic purposes the wind action on the contact wire is decomposed into two contributions. The first is a quasi-steady mean component associated with the average wind speed and the static aerodynamic lift–drag coefficients; this component shifts the equilibrium position of the contact wire but contributes only weakly to the high-frequency contact force fluctuation. The second is a stochastic turbulent component, modelled as a zero-mean broadband random process whose spectral content overlaps with the dominant vertical mode of the contact wire. Within the proposed reduced-order framework, the contact loss probability and the contact force standard deviation are governed almost entirely by the stochastic turbulent component, while the quasi-steady part influences mainly the static deflection and the mean contact force level. Vortex-induced and galloping responses, when relevant, are interpreted as narrow-band amplifications of this stochastic component near the dominant natural frequency. This explicit decomposition is important because treating wind as a purely steady-state lift force would systematically underestimate the contact loss probability, whereas treating it as a single broadband turbulent excitation without the quasi-steady term would distort the static deflection and the mean contact force prediction.

In the proposed framework, wind-induced vibration and galloping are not treated as independent aerodynamic design problems. They are introduced as external excitation terms $Q_w(t)$ acting on the reduced contact-wire coordinate in Eq. (4). Their influence is evaluated through the resulting increase in contact-wire displacement, contact force fluctuation, and probability of temporary contact loss. Therefore, wind effects are directly connected with pantograph-contact wire dynamics through the contact force indicator $F_{int}(t)$.

### 3.2. Structural parameter degradation and reliability-oriented indicators

During long-term operation, the elastic and geometric parameters of overhead contact line components may change because of wear, loosening of structural connections, creep effects, and progressive degradation of supporting elements. Even moderate changes in equivalent stiffness may significantly alter natural frequencies, dynamic deflections, and contact force behaviour [1], [11], [14].

It should be clarified that the equivalent stiffness reduction adopted in the present formulation represents a spanwise-averaged, uniform-type degradation of the contact-wire suspension. Localised wear, isolated dropper failure, single-clamp loosening, or a damaged registration arm are not described by a single scalar reduction of kc, because they alter the spatial distribution of compliance rather than its average value. Such localised defects shift the modal shape of the contact wire and excite higher harmonics that are filtered out by the dominant-mode reduction. Consequently, two operating conditions with the same spanwise-averaged stiffness loss but with different defect localisation can produce different contact force spectra, different short-duration peaks of the contact force, and different instantaneous probabilities of contact loss. Within the limits of the present model, the predicted natural-frequency shift, the mean contact force, and the overall contact force fluctuation level remain meaningful trend indicators of cumulative degradation, but localised defect detection and the harmonic signature of localised wear must be assessed separately using a distributed or finite-element pantograph-catenary representation, or directly from monitoring data.

Within the present framework, the contact suspension is interpreted as an equivalent elastic system whose reduced stiffness reflects the current structural condition. This makes it possible to link parameter degradation with changes in the dynamic response of the reduced-order model.

In the present study, reliability-oriented indicators are not treated as direct field-validated measures of the entire infrastructure system. Rather, they are introduced as analytical performance indicators derived from the reduced-order model and used to compare the influence of parameter changes on system behavior:

$$k_{eq} = \frac{F}{\delta}. \tag{10}$$

The dynamic behavior of the system during interaction with the pantograph can be described by the reduced-order equations of motion Eqs. (4)-(6), where the stiffness parameters directly reflect the current technical condition of the suspension.

Changes in elasticity lead to variations in the system's natural frequencies $\omega_n$, in rad/s:

$$\omega_n = \sqrt{\frac{k_{eq}}{m}}, \tag{11}$$

where $k_{eq}$ is the equivalent stiffness of the system, N/m; $m$ is the mass of the system, kg.

This, in turn, can lead to approaching resonance conditions and an increase in dynamic loads. As a result, the rate of damage accumulation and the probability of failures increase.

For assessing reliability over time, the following relationship is used:

$$R(t) = \exp\left(-\int_0^t \lambda\left(\tau; k_{eq}\right) d\tau\right), \tag{12}$$

where $R(t)$ is the probability of failure-free operation over time $t$; $\lambda\left(\tau; k_{eq}\right)$ is the failure rate, 1/s; $\tau$ is the integration time variable from 0 to the current time $t$; exp denotes the exponential function.

Here, the failure rate is considered as a function of the current stiffness. As the elastic properties degrade, it increases, leading to an accelerated decrease in the probability of failure-free operation.

Considering the uncertainty of material properties and operating conditions, the problem is often formulated probabilistically using a limit state function:

$$R_f = P(g(X) \leq 0), \tag{13}$$

where $R_f$ is the probability of failure; $P$ is the probability operator; $g(X)$ is the limit state function.

This interpretation allows the analyst to evaluate how stiffness degradation affects dynamic behaviour and to estimate preliminary reliability-oriented trends. Such results may be used for comparative diagnostics and condition-based prioritization, while full practical implementation still requires calibration using monitoring data.

Therefore, stiffness degradation is directly linked to pantograph-contact wire dynamics through the equivalent stiffness kc of the reduced contact-wire coordinate. A decrease in kc changes the natural frequency, modifies the dynamic response to pantograph excitation, and may increase contact force fluctuation and contact loss risk. In this way, structural degradation is not considered as an isolated reliability problem, but as a factor that directly affects current collection stability.

### 3.3. Electrical-thermal effects

In addition to mechanical vibration effects, railway overhead contact lines are influenced by electrical operating conditions. Increased contact resistance, unstable electrical contact, and local current concentration may cause additional heating, material ageing, and accelerated degradation [4], [13]. In a simplified diagnostic interpretation, the heat generation effect may be represented as:

$$P = I^2 R, \tag{14}$$

where $I$ is the current magnitude and $R$ is the electrical resistance of the contact element.

In the proposed framework, electrical-thermal effects are not considered as an independent thermal design problem. They are included as degradation accelerators that may increase contact resistance, intensify local heating, reduce mechanical reliability, and indirectly increase the probability of unstable current collection. Thus, electrical-thermal deterioration is linked with pantograph–contact wire dynamics through its influence on degradation rate and reliability-oriented indicators.

### 3.4. Pantograph-contact wire interaction

Pantograph-contact wire interaction is the central output mechanism of the proposed framework. Wind excitation, stiffness degradation, and electrical-thermal deterioration are interpreted through their influence on the contact force between the pantograph head and the contact wire. Therefore, the main diagnostic indicators are contact force variation, probability of contact loss, and reliability-oriented degradation trends.

The interaction force is calculated using the relative displacement and velocity between the pantograph head and the dominant contact-wire coordinate, as shown in Eq. (6). Stable current collection requires the contact force to remain positive during operation. If $F_{int}(t)$ becomes zero or negative, temporary contact loss may occur, which can cause arcing, increased wear, and deterioration of current collection quality.

### 3.5. Illustrative parametric example

To demonstrate the diagnostic logic of the revised reduced-order framework, the illustrative example is reformulated in terms of contact-force-related indicators. The numerical values are illustrative and are used only to show how stiffness degradation may influence the dominant vibration response, contact force fluctuation, probability of contact loss, and preliminary reliability indicators.

The baseline equivalent stiffness of the contact-wire subsystem is assumed as $k_c = 1200$ N/m. Several stiffness degradation levels are considered. The mean contact force is assumed to remain approximately constant, while the standard deviation of the contact force increases as stiffness decreases. This reflects the higher dynamic sensitivity of the degraded contact-wire subsystem.

The selected output indicators, namely mean contact force, contact force standard deviation, and probability of contact loss, are directly related to the quality of pantograph-contact wire interaction. Therefore, even though the numerical example is illustrative, it is formulated in terms of practically interpretable diagnostic quantities rather than purely abstract vibration parameters.

**Table 2.** Influence of stiffness degradation on reduced pantograph–contact wire diagnostic indicators

| Stiffness loss, % | $k_c$, N/m | $\omega_n$, rad/s | Mean contact force, N | Contact force SD, N | $P\ (F_{int} \leq 0)$ | R(100) |
|---|---|---|---|---|---|---|
| 0 | 1200 | 28.28 | 70 | 12 | 0.010 | 0.905 |
| 10 | 1080 | 26.83 | 70 | 15 | 0.018 | 0.894 |
| 20 | 960 | 25.30 | 70 | 19 | 0.032 | 0.882 |
| 30 | 840 | 23.66 | 70 | 24 | 0.055 | 0.866 |

The results show that stiffness degradation does not only reduce the natural frequency of the contact-wire subsystem, but also increases contact force fluctuation. As the stiffness decreases, the reduced model predicts a higher probability of temporary contact loss. This directly links the degradation process with pantograph-contact wire interaction and demonstrates the diagnostic purpose of the reduced-order framework.

It should be emphasized that the example is not intended as a validated full-scale simulation of a specific railway line. Its purpose is to demonstrate how the reduced-order model can be used for preliminary sensitivity analysis and for identifying potentially critical operating conditions that require further detailed modelling or field validation.

## 4. Discussion and limitations

The revised framework clarifies that the proposed reduced-order model is intended for preliminary diagnostic assessment rather than detailed design-level simulation of the complete pantograph–catenary system. The overhead contact line is a distributed multi-degree-of-freedom system, and its complete dynamic description requires representation of the contact wire, messenger wire, droppers, supports, nonlinear contact conditions, and wave propagation effects. Therefore, the proposed model should be interpreted as a simplified diagnostic tool for identifying dominant trends rather than as a replacement for high-fidelity numerical simulation.

The main advantage of the proposed approach is that it preserves a physically interpretable link between structural degradation, vibration response, contact force variation, and reliability-oriented indicators. Stiffness degradation is reflected in the equivalent modal stiffness of the dominant contact-wire coordinate. Wind-induced vibration is introduced as an external excitation term, while electrical-thermal effects are interpreted as degradation accelerators. These mechanisms are connected through their influence on the contact force between the pantograph head and the contact wire.

The two-coordinate reduced model is an important improvement compared with a purely one-degree-of-freedom approximation. It includes both the dominant displacement of the contact wire and the vertical displacement of the pantograph head. This makes it possible to estimate relative motion, contact force variation, contact loss probability, and contact-stability-related reliability indicators.

At the same time, the model has several limitations. It does not reproduce all higher vibration modes, local dropper behaviour, nonlinear aerodynamic effects, detailed pantograph multi-body dynamics, spatial irregularities, or wave propagation along the contact line. The illustrative numerical example is based on assumed representative parameters and is used only to demonstrate the diagnostic logic of the framework. For practical implementation, the model must be calibrated and validated using measured contact force, contact wire displacement, benchmark simulations, or operational monitoring data.

In addition to the general modelling restrictions listed above, two specific assumptions should be made explicit. First, structural stiffness degradation is represented as a spanwise-averaged uniform reduction of the equivalent modal stiffness; localised wear, single-point damage, or isolated component failure are outside the scope of the dominant-mode reduction and may produce harmonic contact force responses that the present model cannot reproduce. Second, wind loading is represented through a quasi-steady mean component and a stochastic turbulent component acting on the contact-wire coordinate; non-stationary aerodynamic phenomena, spanwise-correlated gusts, and full vortex-shedding feedback are not modelled. The benchmark-type comparison given in Section 2.2 indicates that the dominant first-mode response is reproduced within an acceptable error range for diagnostic use, but the deviations grow for higher-order statistics of the contact force, where higher modes and localised effects contribute substantially. Therefore, the present framework should be used for screening, prioritisation, and sensitivity studies, while quantitative design-level decisions still require validated distributed pantograph-catenary models or field measurements.

## 5. Conclusions

This study proposed a reduced-order diagnostic framework for preliminary assessment of pantograph-contact wire vibration response and reliability-oriented indicators. The revised formulation clarifies that the overhead contact line is a distributed multi-degree-of-freedom system and that the reduced model is not intended to replace full pantograph-catenary simulation.

A key element of the framework is the two-coordinate reduced model, which includes both the dominant contact-wire displacement and the pantograph head displacement. This formulation makes it possible to evaluate contact force variation, contact loss probability, and stiffness-dependent reliability trends. Therefore, the proposed model is directly linked to pantograph-contact wire dynamics rather than being limited to a one-degree-of-freedom vibration approximation.

Wind-induced excitation, structural stiffness degradation, and electrical-thermal deterioration are interpreted through their influence on contact force stability. The illustrative example shows that stiffness degradation may reduce natural frequency, increase contact force fluctuation, and raise the probability of temporary contact loss.

The main limitation of the study is the simplified nature of the reduced-order representation. Higher vibration modes, local structural effects, nonlinear contact behaviour, detailed aerodynamic phenomena, and spatial irregularities are not fully captured. Further work should focus on calibration and validation using field measurements, benchmark pantograph–catenary simulations, and extended nonlinear models.

## Acknowledgements

The authors have not disclosed any funding.

## Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Conflict of interest

The authors declare that they have no conflict of interest.

## References


**[1]** J. Mulder, F. Vahdatikhaki, X. Yin, F. Vermeulen, and H. Voordijk, "Predicting the wear rate and thickness of train contact wire using data-driven modelling," *Applied Sciences*, Vol. 15, No. 17, p. 9362, 2025, https://doi.org/10.3390/app15179362

**[2]** E. R. Prasetiyo, S. Wicaksono, T. D. Rachmilda, and V. Virdyawan, "Reliability improvement of overhead catenary system for electric train: a review," *Jurnal Perkeretaapian Indonesia (Indonesian Railway Journal)*, Vol. 9, No. 1, pp. 44–56, 2025, https://doi.org/10.37367/jpi.v9i1.316

**[3]** B. Rodríguez-Arana, P. Ciáurriz, N. Gil-Negrete, and U. Alvarado, "A non-intrusive monitoring system on train pantographs for the maintenance of overhead contact lines," *Sensors*, Vol. 23, No. 18, p. 7890, Sep. 2023, https://doi.org/10.3390/s23187890

**[4]** M. Yakubov, M. Talipov, and U. Nurullaev, "An optimized Lagrangian approach to reactive power compensation in nonlinear traction power-supply systems," *Vibroengineering Procedia*, Vol. 60, pp. 724–730, Dec. 2025, https://doi.org/10.21595/vp.2025.25604

**[5]** B. Harsono, F. M. Mahadiva, Tavio, M. M. Talipov, and H. Hermawan, "Pushover analysis of simple house structures in seismic zones," in *AIP Conference Proceedings*, Vol. 3480, No. 1, p. 050035, Mar. 2026, https://doi.org/10.1063/5.0319164

**[6]** M. Talipov, "Computational modeling and analysis of mechanical power consumption in train assemblers' work," in *International Conference on Applied Innovations in IT (ICAIIT)*, Vol. 13, No. 2, pp. 419–426, 2025, https://doi.org/10.25673/120513

**[7]** H. Yudariansyah, Ismiyati, and A. Narendra, "Prediction model for the maintenance of rail infrastructure in Java," *E3S Web of Conferences*, Vol. 429, p. 03004, 2023, https://doi.org/10.1051/e3sconf/202342903004

**[8]** W. Zhou, Z. Qin, X. Du, X. Xue, H. Wang, and H. Li, "Measurement method for contact wire wear based on stereovision," *Sensors*, Vol. 24, No. 7, p. 2085, Mar. 2024, https://doi.org/10.3390/s24072085

**[9]** F. Duan et al., "Study on aerodynamic instability and galloping response of rail overhead contact line based on wind tunnel tests," *IEEE Transactions on Vehicular Technology*, Vol. 72, No. 6, pp. 7211–7220, 2023, https://doi.org/10.1109/tvt.2023.3243024

**[10]** J. He, J. He, Z. Gou, and F. Lv, "Defect detection in railway catenary systems: a survey," *Intelligent Transportation Infrastructure*, Vol. 4, 2025, https://doi.org/10.1093/iti/liaf027

**[11]** S. Kaewunruen, C. Ngamkhanong, and L. Ren, "Reliability quantification of railway electrification mast structure considering buckling," *Frontiers in Built Environment*, Vol. 7, 2021, https://doi.org/10.3389/fbuil.2021.761491

**[12]** A. Takahashi, T. Kishi, and H. Yamamoto, "Overhead contact line monitoring and prediction of contact wire localized wear points," *JR East Technical Review*, Vol. 29, pp. 22–25, 2014.

**[13]** J. A. Sainz-Aja et al., "Real-time rail electrification systems monitoring: a review of technologies," *Sensors*, Vol. 25, No. 21, p. 6625, 2025, https://doi.org/10.3390/s25216625

**[14]** Y. Song, H. Wang, G. Frøseth, P. Nåvik, Z. Liu, and A. Rønnquist, "Surrogate modelling of railway pantograph-catenary interaction using deep Long-Short-Term-Memory neural networks," *Mechanism and Machine Theory*, Vol. 187, p. 105386, 2023, https://doi.org/10.1016/j.mechmachtheory.2023.105386

**[15]** W. Chu, H. Wang, Y. Song, and Z. Liu, "FENet: a physics-informed dynamics prediction model of pantograph-catenary systems in electric railway," *IET Intelligent Transport Systems*, Vol. 19, No. 1, 2025, https://doi.org/10.1049/itr2.70059

**[16]** H. Wang, Y. Song, H. Yang, and Z. Liu, "Generalized Koopman neural operator for data-driven modeling of electric railway pantograph-catenary systems," *IEEE Transactions on Transportation Electrification*, Vol. 11, No. 6, pp. 14100–14112, 2025, https://doi.org/10.1109/tte.2025.3609347

**[17]** Z. Liu, H. Wang, H. Yang, and Y. Song, "A systematic literature review on active control technology of pantograph-catenary system in high-speed railway," *High-speed Railway*, 2025, https://doi.org/10.1016/j.hspr.2025.11.004

**[18]** H. Yang et al., "An electrified railway catenary component anomaly detection frame based on invariant normal region prototype with segment anything model," *IEEE Transactions on Transportation Electrification*, Vol. 12, No. 1, pp. 1391–1402, 2026, https://doi.org/10.1109/tte.2025.3628607