Jurnal Personalia Pelajar 29(1): 251-256
https://doi.org/10.17576/personalia.2901.2026.26
ISSN 0128-2735

Realizing Overhead Line Pantograph Powered for EV −Impact Oscillation Analysis-
(Merealisasikan Pantograf Talian Atas yang Dikuasakan untuk EV −Analisis Ayunan Impak−)

MASAHIRO OKI & HIROSHI YABUNO

ABSTRACT

In-motion charging systems using overhead contact lines and pantographs have attracted increasing attention as a promising solution to overcome driving range limitations and infrastructure challenges faced by battery-powered electric vehicles (EVs). Although such systems have been successfully operated in railway transportation and have recently been demonstrated for road vehicles, maintaining stable mechanical contact between the pantograph and the overhead contact line remains a critical technical challenge. In particular, repeated loss of contact can induce impact oscillations that may compromise system reliability. In this study, the dynamic behavior of an EV equipped with an overhead contact line–pantograph power supply system is investigated through numerical simulations. A simplified two-degree-of-freedom mechanical model is introduced to represent the vertical dynamics of the vehicle body and the pantograph contact strip, taking into account periodic excitation induced by corrugated wear of the overhead contact line. Loss of contact and impacts are modeled using a unilateral contact condition and an impact law with a coefficient of restitution. The numerical results demonstrate that impact oscillations occur when the vehicle running speed exceeds a critical value. The resulting impact response exhibits multi-time-scale dynamics: periodic impacts synchronized with the excitation on a short time scale and amplitude modulation on a longer time scale. These findings indicate that impact oscillations are a non-negligible dynamic phenomenon in pantograph-based in-motion charging systems for EVs and should be considered in system design.

Keywords: EV, Pantograph, Periodic Impacts, Multi-time-scale Dynamics

ABSTRAK

Sistem pengecasan semasa pergerakan yang menggunakan talian sentuh atas dan pantograf semakin mendapat perhatian sebagai satu penyelesaian yang berpotensi untuk mengatasi had jarak pemanduan dan cabaran infrastruktur yang dihadapi oleh kenderaan elektrik (EV) berasaskan bateri. Walaupun sistem sedemikian telah lama digunakan dengan jayanya dalam pengangkutan rel dan baru-baru ini telah diuji untuk kenderaan jalan raya, mengekalkan sentuhan mekanikal yang stabil antara pantograf dan talian sentuh atas masih merupakan cabaran teknikal yang kritikal. Khususnya, kehilangan sentuhan yang berulang boleh menyebabkan ayunan hentaman yang berpotensi menjejaskan kebolehpercayaan sistem. Dalam kajian ini, tingkah laku dinamik sebuah EV yang dilengkapi dengan sistem bekalan kuasa berasaskan pantograf dan talian sentuh atas dikaji melalui simulasi berangka. Satu model mekanikal ringkas dua darjah kebebasan dibangunkan untuk mewakili dinamik menegak badan kenderaan dan jalur sentuh pantograf, dengan mengambil kira pengujaan berkala yang disebabkan oleh haus beralun pada talian sentuh atas. Kehilangan sentuhan dan hentaman dimodelkan menggunakan keadaan sentuhan sehala dan hukum hentaman dengan pekali pemulihan. Keputusan simulasi menunjukkan bahawa ayunan hentaman berlaku apabila kelajuan pemanduan kenderaan melebihi satu nilai kritikal. Tindak balas hentaman yang terhasil memperlihatkan dinamik pelbagai skala masa, iaitu hentaman berkala yang terselaras dengan pengujaan pada skala masa pendek serta modulasi amplitud pada skala masa yang lebih panjang. Dapatan ini menunjukkan bahawa ayunan hentaman merupakan fenomena dinamik yang tidak boleh diabaikan dalam sistem pengecasan semasa pergerakan berasaskan pantograf untuk EV dan perlu dipertimbangkan dalam reka bentuk sistem.

Kata Kunci: EV, Pantograf, Ayunan hentaman, Dinamik berbilang skala masa

INTRODUCTION

In recent years, the promotion of electric vehicles (EVs) has been widely recognized as a crucial step toward achieving a sustainable and decarbonized society, as EVs enable mobility without direct carbon dioxide emissions during operation. However, most currently deployed EVs rely exclusively on onboard batteries, which inevitably impose limitations on driving range and require extensive charging infrastructure. While alternative technologies such as all-solid-state batteries and wireless power transfer systems have been actively explored, each approach still faces practical constraints, including challenges in energy capacity, power transfer efficiency, and large-scale deployment. As a result, there remains a strong demand for innovative power supply solutions that can support the widespread adoption of EVs. Against this background, in-motion charging systems using overhead contact lines and pantographs have attracted increasing attention as a promising next-generation technology. In particular, overhead contact line–pantograph power supply systems have been tested in real-world conditions on public highways in Germany, where demonstration projects for electrified heavy-duty vehicles have been conducted (Schöpp et al., 2022). Such systems have a long history of reliable operation in railway transportation. Nevertheless, even in railway applications, maintaining stable contact between the pantograph and the overhead line is a nontrivial challenge (Amano et al., 2024). Repeated loss of contact can lead to mechanical impacts and oscillations, potentially compromising operational reliability. These issues are therefore expected to become equally important when adapting pantograph-based power supply systems to EVs.

In this study, an EV equipped with a pantograph-based power supply system is represented by a simplified mechanical model, and its dynamic behaviour is investigated through computational analysis. The primary objective of this research is to clarify the conditions under which mechanically contacted power supply systems can operate in a stable and reliable manner, using an established theoretical framework in nonlinear dynamics. By improving the understanding of dynamic stability in in-motion charging systems, this research contributes to reducing technical risks associated with their real-world implementation. Ultimately, such advancements are expected to alleviate driving range constraints and infrastructure-related challenges faced by current EVs, thereby supporting the broader adoption of electric mobility. In this sense, the present study contributes to Sustainable Development Goal 13, “Climate Action,” by addressing a key technological barrier to sustainable transportation systems. Many universities are currently promoting “green campus” initiatives aimed at reducing environmental impacts and advancing sustainability in higher education (Cortese, 2003; Lozano et al., 2013). University campuses can also function as “living laboratories” where sustainable technologies are tested and demonstrated in real-world settings (Evans et al., 2015). Implementing pantograph-based in-motion charging EV systems within university campuses may therefore contribute not only to improving mobility convenience and supporting green campus initiatives but also to providing experiential learning opportunities related to sustainable mobility technologies based on real mechanical systems and to enhancing student’s sustainability awareness. Therefore, understanding the dynamic characteristics and operational stability of EV power supply systems is also relevant for the future implementation of sustainable mobility solutions within campus environments.

ANALYTICAL MODEL

Figure 1(a) illustrates a schematic diagram of the electric vehicle (EV) receiving electric power from an overhead contact line, which is the subject of the present analysis. In this study, a rigid overhead contact line is considered. It is well known that corrugated wear is generated on rigid contact lines due to friction with the pantograph contact strip. This corrugated wear acts as a source of periodic excitation on the contact strip. Taking into account the periodic excitation characteristics induced by the corrugated wear, the system is modeled as shown in Figure 1(b). In this model, the suspension supporting the vehicle body and the pantograph frame supporting the contact strip are represented as equivalent linear springs, and damping effects are neglected. The vehicle body and the contact strip are modeled as lumped masses that move only in the vertical direction. Rotational motion of the vehicle body, such as pitching, and variations in the pantograph angle are not considered. In addition, situations in which the vehicle body loses contact with the ground are excluded, and the spring corresponding to the suspension is assumed to be fixed to the reference coordinate system.

(a) Schematic diagram of an electric vehicle (EV) receiving electric power from a rigid overhead contact line via a pantograph. (b) Simplified mechanical model used in the present analysis, where the vehicle body and the contact strip are represented as lumped masses connected by linear springs.

The physical parameters of the two-degree-of-freedom model used in the numerical simulations are listed in Table 1.

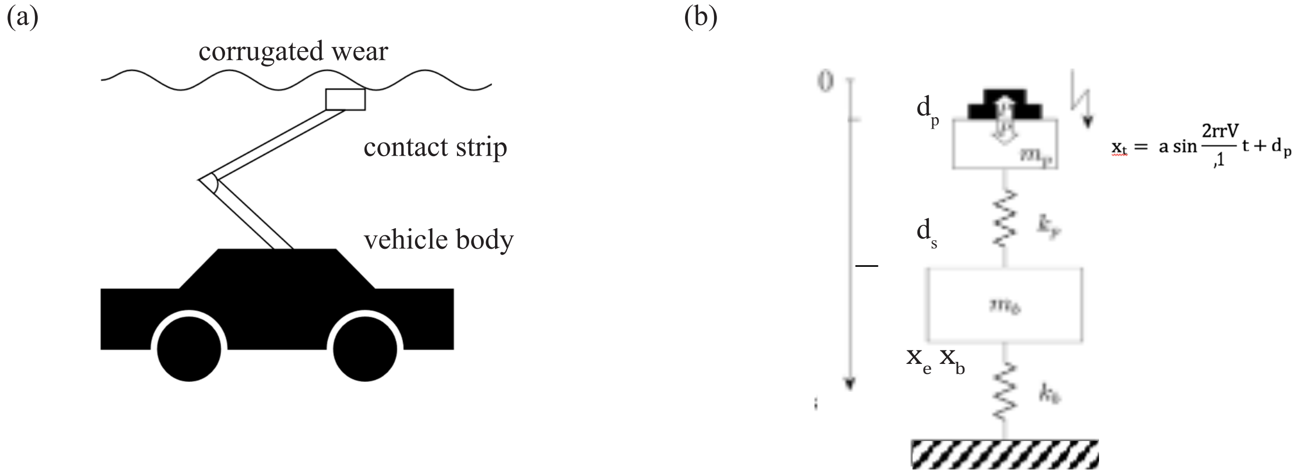

FIGURE 1. Schematic diagram and mechanical model

TABLE 1. The physical parameters used in the numerical simulations

Name	Symbol	Value
Mass of contact strip	m_e	10 kg
Mass of vehicle body	m_b	3000 kg
Equivalent spring stiffness of pantograph	k_p	15000 N/m
Equivalent spring stiffness of suspension	k_s	30000 N/m
Amplitude of corrugated wear	a	0.25 mm
Period of corrugated wear	,1	20 cm
Initial indentation of suspension	d_s	4 mm

THE EQUATIONS OF MOTION

In normal operation, the pantograph is pressed against the overhead contact line in order to maintain continuous contact. The contact strip receives the reaction force corresponding to this pressing force, which is denoted by P(t). Considering this reaction force, the restoring forces exerted on the contact strip and the vehicle body by the equivalent spring representing the pantograph, and the restoring force exerted on the vehicle body by the equivalent spring representing the suspension. Then the equations of motion for the vertical displacements of the contact strip and the vehicle body can be written as follows:

$$m_e \ddot{x}_e + k_p x_e - k_p x_b = P(t), \quad (1)$$

$$m_b \ddot{x}_b - k_p x_e + (k_p + k_s) x_b = 0, \quad (2)$$

where the vertical displacements of the contact strip and the vehicle body are denoted by x_e and x_b, respectively.

NONDIMENSIONALIZATION

The governing equation of motion given in Eq. (1), (2) and x_t are nondimensionalized in this section. By introducing nondimensional variables, the equation of motion can be reformulated in a form that is not restricted to a specific physical scale. This procedure reduces the number of independent parameters and allows the essential dimensionless parameters governing the system dynamics to be identified. To perform nondimensionalization, characteristic scales for length and time must be defined. These characteristic length and time scales serve as reference quantities for rescaling the variables in the governing equation. In this study, the characteristic length is defined as d_s, and the characteristic time is defined as $\sqrt{m_b/k_s}$. Using these characteristic scales, the nondimensional variables are defined as follows:

$$x_c^* = \frac{x_c}{d_s},\ x_b^* = \frac{x_b}{d_s},\ x_t^* = \frac{x_t}{d_s},\ t^* = \sqrt{\frac{k_s}{m_b}}\, t,\ P^* = \frac{P}{k_s d_s}\ .$$

Using these definitions, Eq. (1), (2) and x_t can be rewritten in the following nondimensional form:

$$\mu \ddot{x}_c^* + \kappa x_c^* - \kappa x_b^* = P^*(t^*)\,, \qquad (3)$$

$$\ddot{x}_b^* - \kappa x_c^* + (\kappa + 1) x_b^* = 0\,, \qquad (4)$$

$$x_t^* = \varepsilon \sin \omega\, t^* + \frac{1+\kappa}{\kappa}\,, \qquad (5)$$

where, μ, κ, $\mathcal{E}$ and ω are nondimensional parameters representing the mass ratio between the contact strip and the vehicle body, the stiffness ratio between the pantograph and the suspension, the nondimensional amplitude of the corrugated wear, and the nondimensional excitation frequency, respectively, defined as follows

$$\mu = \frac{m_c}{m_b}, \kappa = \frac{k_p}{k_s}, \varepsilon = \frac{a}{d_s}, \omega = \frac{2\pi V}{\lambda}\sqrt{\frac{m_b}{k_s}}$$

In Eq. (5), the constant offset d_p is determined from the static equilibrium condition corresponding to the initial preload state, such that $d_p = {}^{\kappa+1/\kappa}\, d_s$. Accordingly, the offset is nondimensionalized as $d_p/d_s = {}^{\kappa+1}/\kappa$. In the following, the asterisk (∗) denoting nondimensional quantities is omitted unless otherwise stated.

THE CONDITION FOR LOSS OF CONTACT AND REACTION FORCE

When the reaction force P(t) included in the equations of motion becomes less than or equal to zero, the contact strip loses contact with the overhead contact line, and the system transitions to a state known as impact oscillation, in which loss of contact and impacts occur repeatedly. During loss of contact, P(t) is set to zero. In this section, the reaction force P(t) is expressed in terms of nondimensional parameters, and the condition for loss of contact is examined. When the contact strip maintains continuous contact with the overhead contact line, its displacement coincides with that of the rigid contact line with corrugated wear, as follows:

$$x_c = x_t = \varepsilon \sin \omega\, t + \frac{1+\kappa}{\kappa}\ . \qquad (6)$$

This condition reflects the fact that, during continuous contact, the contact strip is kinematically constrained to follow the vertical displacement of the rigid overhead contact line. Substituting this condition into Eq. (4), the following equation is obtained:

$$\ddot{x}_b + (\kappa + 1) x_b = \kappa \varepsilon \sin \omega\, t + (\kappa + 1)\,. \qquad (7)$$

Solving this equation for x_b, x_b is obtained as follows:

$$x_b = A \cos(\sqrt{\kappa+1}\, t + \phi) + \frac{\kappa \varepsilon}{(\kappa+1) - \omega^2} \sin \omega t + 1\,, \qquad (8)$$

where constants $\boldsymbol{A}$ and $\boldsymbol{\phi}$ appearing in this expression are determined by the initial conditions of the vehicle body. Substituting Eqs. (6) and (8) into Eq. (3), the equation for the motion of the contact strip, the reaction force $\boldsymbol{P(t)}$ can be written as follows:

$$P(t) = \kappa\left(1 - \frac{\omega^2}{\kappa} - \frac{\kappa}{(\kappa + 1) - \omega^2}\right)\varepsilon \sin \omega t - \kappa A \cos\left(\sqrt{\kappa + 1}\, t + \phi\right) + 1 . \quad (9)$$

From Eq. (9), the reaction force $\boldsymbol{P(t)}$ under contact conditions is composed of a periodic excitation term induced by corrugated wear, a component associated with the natural frequency that depends on the initial conditions, and a constant term. The constant term corresponds to the reference reaction force given by the characteristic force $k_s d_s$ used in the nondimensionalization. Therefore, the maintainability of the contact condition can be evaluated based on the relative contributions of the fluctuating terms to this reference force, that is, by the sign of $\boldsymbol{P(t)}$. Furthermore, the coefficient of the external excitation term is expressed as a function of K and w, and it includes the term $(K + 1) - w^2$ in the denominator. This indicates that variations in w, and hence in the vehicle running speed V, can significantly influence the reaction force and play a crucial role in the onset of loss of contact.

CHANGE BEFORE AND AFTER IMPACT

The impacts are assumed to occur instantaneously and to cause discontinuous changes in velocity according to the impact law given below,

$$\dot{x}_c^+ = -\alpha \dot{x}_c^- + (\alpha + 1)\, \dot{x}_t , \quad (10)$$

where a denotes the coefficient of restitution. The impact law adopted here is similar to that used in classical bouncing-ball models (Holmes, 1982). Based on the above fundamental equations, reaction force, and impact law, time-domain numerical simulations were carried out for several vehicle running speeds.

ANALYTICAL RESULTS

Figure 2 shows the time histories of the system response for different vehicle running speeds. Figure 2(a) presents the time history at a running speed of 10 km/h. At this low speed, loss of contact does not persist, and the impact oscillation eventually disappears, resulting in continuous contact between the contact strip and the overhead contact line. Figures 2(b) and 2(c) show the time histories at a running speed of 40 km/h on different time scales. Figure 2(b) shows a short-time-scale view of the response, in which periodic impacts of the contact strip occur once per period of the corrugated wear. This indicates that the impact oscillation is synchronized with the excitation induced by the corrugated wear. Figure 2(c) presents a long-time-scale view of the same response. Although the impacts occur periodically on a short time scale, the amplitude of the impact oscillation exhibits a slow modulation over a longer time scale, resulting in a beat-like waveform.

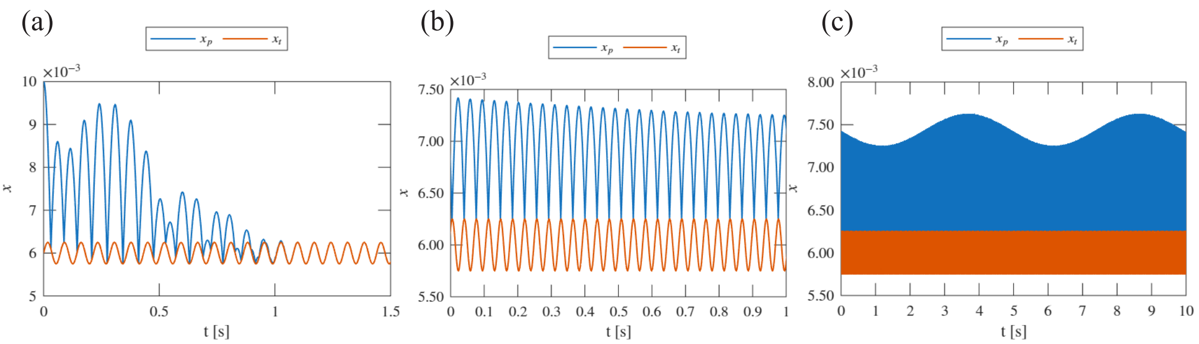

FIGURE 2. Time histories of the system response for different vehicle running speeds

(a) Time history at 10 km/h, where loss of contact does not persist and the impact oscillation eventually disappears. (b) Short-time-scale view of the response at 40 km/h, showing periodic impacts of the contact strip synchronized with the excitation caused by corrugated wear. (c) Long-time-scale view of the response at 40 km/h, illustrating amplitude modulation of the impact oscillation.

CONCLUSION

In this study, numerical simulations were conducted to investigate the dynamic behaviour of an electric vehicle equipped with an overhead contact line–pantograph power supply system. The results demonstrate that impact oscillation occurs when the vehicle running speed exceeds a certain critical value. Furthermore, the resulting impact oscillation exhibits multi-time-scale dynamics: on a short time scale, impacts occur periodically in synchrony with the excitation induced by corrugated wear, while on a longer time scale, the oscillation amplitude undergoes periodic modulation. The analytical expression of the reaction force indicates that it contains multiple frequency components, including those associated with the external excitation and the intrinsic dynamics of the vehicle body, which provides a theoretical basis for the emergence of such multi-time-scale behaviour. These findings indicate that impact oscillation is a non-negligible dynamic phenomenon in overhead contact line–pantograph power supply systems for EVs and should be taken into account in system design. Future work will focus on bifurcation analysis of the impact oscillation to systematically clarify the relationship between design parameters and the critical running speed, as well as the dynamic characteristics of the resulting impact responses. Such analyses are expected to contribute to the identification of stable operating conditions and to provide a technical foundation for the practical implementation of overhead contact line–pantograph power supply systems for electric vehicles.

These findings may also support future implementation of pantograph-based in-motion charging systems in campus environments, where such systems could serve both as sustainable mobility infrastructure and as educational platforms for sustainability-oriented technologies.

ACKNOWLEDGEMENTS

The authors would like to express gratitude to this research which has been supported by the JST SPRING program at the University of Tsukuba.

REFERENCES

Amano, Y., Kobayashi, S., Yabuno, H., Yamashita, Y., & Mori, H. (2024). Mechanism *and suppression of friction-induced vibration in* catenary–pantograph system. Nonlinear Dyn 112, 14959–14980.

Cortese, A. D. (2003). The critical role of higher education in creating a sustainable future. Planning for Higher Education, 31(3), 15–22.

Evans, J., Jones*, R., Karvone*n*, A.*, Millard, L., & Wendler, J. (2015). Living labs and co-production: University campuses as platforms for sust*ainabilit*y *science. Current Opini*on in Environmental Sustainability, 16, 1–6.

Holmes, P. J. (1982). The dynamics of repeated impacts with a sinusoidally vibrating table. Journal of Sound and Vibration, 84(2), 173–189.

Lozano, R., Lukman, R., *Lozano, F. J., Hui*singh*, D., & La*mbrechts, W. (2013). Declarations for sustainability in higher education: Becoming better leaders through addressing the university system. Journal of Cleaner Production, 4*8, 10–1*9.

*Schöp*p, F.*, Worbs, M., Bulenda, A., Bu*rger*t, T., Öztürk, Ö., & Linke, R. (2022). Current technical findings on the eHighway system. Institut*e for E*nergy *and Environmental* Res*earch (ifeu).

Masahiro Oki* & Hiroshi Yabuno
Graduate School of Science and Technology,
University of Tsukuba,
1-1-1 Tennodai, Tsukuba,
Ibaraki 305-8577 Japan.

*Corresponding author: s2530176@u.tsukuba.ac.jp