Three-dimensional Simulation of Catenary/Pantograph Dynamic Interaction

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Simulation of Catenary/Pantograph dynamic interaction is used for understanding the dynamic behavior of overhead contact lines (OCL) and pantographs, and stability to supply electric power to a vehicle. The authors developed a new simulation tool using a three-dimensional model of OCL and a pantograph, which can calculate their full three-dimensional dynamic behavior. Each node in the OCL model has 6 degrees of freedom; this tool can evaluate contact quality between the OCL and a pantograph system even on curved sections. Furthermore, it can evaluate the expansion/contraction of OCL due to temperature change, which affects contact quality. This paper describes this simulation tool in detail, through the example of an analysis of the contact between contact lines and a pantograph from the results of a simulation of a pantograph passing a crossing section.

Keywords: pantograph, overhead contact lines, three-dimensional simulation, contact analysis, current collection, crossing section

1. Introduction

In electric railways around the world, overhead contact lines (OCL) and pantographs are widely used as a system for supplying electric power to rolling stock. To supply stable power to rolling stock, it is necessary to have a proper understanding of the dynamic behavior of OCL and pantographs. To this end, theoretical analyses [1] and numerical simulations have been conducted. Numerical simulations are indispensable for quantitative evaluations considering non-linear phenomena such as contact loss (i.e. a pantograph loses contact with contact wire) and dropper slackening (i.e. a dropper lifts from messenger wire due to the upward force of the pantograph). Consequently, many numerical simulation tools have been developed around the world [2].

In Japan, in the latter half of the 1960s, Ehara et al. developed a simulation method for catenary/pantograph dynamic interaction using the finite difference method (FDM). In this method, the OCL is modeled as lumped masses and strings connecting them. RTRI continued making improvements to this simulation method [3, 4, 5]. In addition, in around 2010, RTRI developed another kind of simulation tool based on the finite element method (FEM) where an OCL above a straight track was modeled as beam elements [5]. In the former, each lumped mass constituting the OCL had single degree of freedom (SDOF), i.e. displacement in the vertical direction; in the latter, each node in the OCL elements has 4 DOF, i.e. displacements and rotational angles in the vertical and lateral direction of the track. Thus, the latter method can reproduce dynamic interaction between pantographs and OCL with three-dimensional (3D) geometry under the condition of strong cross wind. Both methods assume that pantographs run on a straight track and are modeled by lumped masses and springs.

However, more complicated simulations, such as for an OCL above a turnout section, require a full three-dimensional dynamic analysis for both OCL and pantographs. To analyze the dynamic behavior of OCL and pantographs in these sections, the following models and analysis methods are required:

- Multiple OCL models in one 3D space to reproduce overlap section or crossing section
- OCL model installed in curved sections
- Pantograph model with width in the lateral direction to the track to reproduce the transition to an OCL above a main line from one above a side line
- A method to calculate the running trajectory of a pantograph along the shape of the track
- Contact analysis method for calculating the 3D contact between the OCL and pantograph

The purpose of this study therefore, is to construct an OCL model which can be installed on a track of any shape that includes curved and gradient sections [6, 7] and a pantograph model which can reproduce 3D motion [8], and develop a full three-dimensional OCL/pantograph simulation by integrating these two models [9]. This paper introduces a new dynamic analysis method (hereinafter “the proposed method”), which can reproduce full three-dimensional dynamic behavior of pantographs and an OCL installed above any kind of track including curved track or turnouts, and presents some calculation results.

2. OCL Model and Pantograph Model

This section outlines the 3D OCL and 3D pantograph models [6, 7, 8]. Hereinafter, X and Y show the horizontal axes and Z shows vertical axis in 3D space, respectively. In addition, the tangential direction of the track center line

is defined as “running direction”; the lateral direction of track, “lateral direction”; and the direction orthogonal to running direction and lateral direction, “vertical direction”.

2.1 OCL model

The OCL is constructed as a 3D FEM model. Contact wire, messenger wire, and OCL fittings (e.g. droppers) are modeled as beam elements considering bending, expansion/contraction, and twisting deformation (Fig. 1). This model reproduces dropper slackening by giving independent nodes both to dropper top and the messenger wire, and inserting springs between them. Specifically, three springs for three directions with different action directions are inserted between the dropper top and the messenger wire nodes. In the running and lateral directions to the track, linear springs with a large spring constant are inserted. In the vertical direction, to reproduce the dropper slackening, a non-linear spring is inserted. Its spring constant was set to 0 N/m for when the dropper lifts from the messenger wire, and 1×10^5 N/m for when the dropper is in contact with the messenger wire.

For wires such as the contact wire, the boundary conditions needed for structural analysis are given depending on the composition of the anchoring device. In the case of fixed terminations, the displacements of the end of the line in all directions (running, lateral, and vertical direction) are constrained. In the case of a compensated line with an automatic tensioning device, a nominal tension is applied in an axial direction of the line while the displacement in the direction perpendicular to the axis is being restrained.

The OCL model features the following:

- The OCL model can be built on a track of arbitrary line shape including curved and gradient sections.
- It can evaluate the dynamic behavior of the OCL in a section with intersecting wiring (e.g. crossing section).
- It can evaluate the influence of dropper slackening.
- It can reproduce OCL structure changes due to temperature changes, by calculating the expansion/contraction of the line with a given coefficient of linear expansion.
- It can reproduce bending due to cross wind (wind from a lateral direction).

2.2 Pantograph model

The pantograph is modeled with 3D beam elements, in the same manner as the OCL model. However, since the pantograph has mechanical linkages, the model to reproduce this mechanism was constructed (Fig. 2) [8, 10]. The panhead is restrained by guides and stoppers so that the panhead does not shift more than a certain amount from its supporting parts on the top of the articulated arm (e.g. cross bar in Fig. 2). Thus, the pantograph model used in this paper considers the spring stroke limit (hereinafter “stopper”) similar to the previously reported model [6].

The node marked as “reference point” is constantly monitored. The spring constant of the non-linear spring switches from 0 N/m to 1×10^5 N/m generating a restoring force, when the reference point comes into contact with the stopper. As shown in the enlarged drawing of Fig.2, the stopper was modeled using a non-linear spring.

3. OCL/Pantograph Simulation Method

The 3D OCL/pantograph simulation was constructed by combining the OCL and the pantograph models described above. Figure 3 shows a flow chart describing the calculation condition setting and the calculation procedure.

In this simulation, the following parameters are required:

- OCL conditions, including the span length, the Young’s modulus of the line, etc.
- Pantograph conditions, including design and material of the pantograph;
- Track conditions, including the curve radius, gradient, and cant of the track;
- Operating conditions, including pantograph running speed.

In addition to these parameters, environmental conditions, including the temperature change (for reproducing the change in the OCL structure caused by the temperature change) and/or the cross wind speed (for reproducing bending of OCLs caused by cross wind), are set. Using these parameters, the 3D OCL and pantograph models are generated. Apart from this procedure, the running trajectory of the base point of pantograph (Fig. 2) is calculated from the track conditions and operating conditions in advance, to obtain the position and orientation of the whole pantograph in the 3D space resulting in the boundary condition of the pantograph model. Then, by using the OCL and pantograph models with the boundary conditions, dynamic simulation of OCL/pantograph is conducted.

It should be noted that the OCL and pantograph are also affected by external factors, e.g. car body vibration and air flow around the pantograph. Therefore, the authors ensured that the proposed method was capable of performing coupled simulations (one-way coupling) with the following two simulators in order to consider effect of car body vibra-

Fig. 1 3D OCL model with beam elements

Fig. 2 3D pantograph model with beam elements

Fig. 3 OCL/pantograph simulator calculation procedure

tion and air flow: first is the vehicle dynamics simulator which can calculate the car body vibration [11]. By coupling with this simulator, it is possible to perform a simulation that reproduces the vibration of the entire pantograph due to car body vibration. Second, is the air flow simulator which can calculate the one-dimensional air flow velocity around the pantograph on entering into a tunnel and inside a tunnel [12]. By coupling with this simulator, it is possible to perform a simulation that takes into account the change of aerodynamic lift force of the pantograph when entering a tunnel.

3.1 Contact analysis

To conduct a dynamics analysis considering OCL/pantograph interaction, an OCL/pantograph contact analysis is necessary. There are two typical contact analysis methods: constraint contact formulation and elastic contact formulation (in other words, penalty method). The latter, easy to use, was applied to this simulator, where contact stiffness consisting of a non-linear spring and a damper is connecting the contact wire to the panhead or the horn. In order to consider three-dimensional geometry of contact wire and pantograph (e.g. stagger and slope of contact wire, rolling and pitching motion of panhead), this analysis assumes that the direction of the contact force is orthogonal to the axial directions of both the panhead and the contact wire (Fig. 4).

The OCL/pantograph contact force represented by the constant stiffness, F_{cont} , is calculated by (1):

$$F_{\text{cont}} = \alpha x_r + \beta \dot{x}_r \quad (1)$$

where α and β are the spring constant and damping constant of the non-linear spring and damper, respectively, and x_r is the contact force acting direction component of relative displacement, in other words amount of penetration, between the control points on the OCL model and on the pantograph model. The dot over the variable represents the time derivative, and the number of dots indicates the order of the derivative. The non-linear characteristics of contact mechanics are given so that α is set to the positive value (50,000 N/m) during contacting or 0 N/m during contact loss and β is set to the positive value (10,000 Ns/m) if the pantograph is in contact with the OCL and moves in the direction for penetrating the OCL or 0 Ns/m otherwise.

The following procedures are used to identify contact pairs, search for contact points, and determine the direction of the contact force. To identify a contact pair, we follow the steps below:

Fig. 4 Schematic diagram of the contact force action direction

Fig. 5 Action direction of the contact force between elements

- 1) Calculate a temporary contact force direction, $\mathbf{n}_p' (= \mathbf{t}_t' \times \mathbf{t}_p')$, where $\mathbf{t}_t'$ is direction vector of the line segment (blue dashed line in Fig. 5) that connects the nodes at both ends of the contact wire element; $\mathbf{t}_p'$, direction vector of the line segment (green dashed line in Fig. 5) that connects the nodes at both ends of the panhead element,
- 2) Project these segments onto a plane vertical to the temporary contact force direction $\mathbf{n}_p'$,
- 3) Check whether the projected line segments have an intersection.

If they intersect, this determines that these elements are a contact pair. Otherwise, we change the elements to search for an intersection, and repeat the process until an intersection is found.

After the intersection is determined, the coordinates and velocity in the 3D space at each contact point on contact wire and panhead are calculated. The calculation is performed based on the state quantity vector of each node, the coordinate transformation matrix for conversion from the element coordinate system to the global coordinate system, and so on. From these coordinates and velocity, the α and β values are selected, corresponding to states of contact or contact loss and the direction of the relative velocity, and the contact force is calculated using (1). At this time, the tangent vectors $\mathbf{t}_t$ and $\mathbf{t}_p$ of the contact wire and panhead elements at the contact point are calculated, and the direction of the contact force, $\mathbf{n}_p$, is calculated anew from the cross product of $\mathbf{t}_t$ and $\mathbf{t}_p$ (Fig. 5). In solving the equation of motion by numerical integration later, the contact force is expressed in a vector format described by the product of the state quantity vector of all nodes and the contact matrix.

3.2 Solution of the equation of motion

Equation (2) is the equation of motion for the OCL/pantograph dynamic simulation.

$$\mathbf{G}_m + \mathbf{G}_c + \mathbf{G}_k = \mathbf{F} + \mathbf{F}_{\text{cont}} \quad (2)$$

where $\mathbf{G}_m$, $\mathbf{G}_c$, and $\mathbf{G}_k$ represent the inertial force, damping force, and restoring force, respectively, of the entire system including the OCL and pantograph. $\mathbf{F}$ represents an external force such as a static uplift force of the pantograph, reaction forces at the supporting points of OCS, and the tension for each wire. $\mathbf{F}_{\text{cont}}$ represents the contact force expressed in vector form.

This equation of motion is solved by numerical integration (Newmark- β method); however, since (2) contains non-linear terms, the convergence calculation (Newton-Raphson method) is performed. The convergence calculation is repeated until the non-equilibrium force of each node occurring due to the geometric non-linearity of the OCL and pantograph becomes to a negligible degree or less.

As described above, in each calculation step, the penalty coefficients α and β are updated depending on the OCL/pantograph contact state (contacting/contact loss; and positive/negative of relative velocity), and the spring and damping constants between droppers and the messenger wire are also updated according to the contact state (contacting/slackening) of them. However, if a value related to the contact state, such as a penalty coefficient, is updated during the process of convergence calculation, the calculation may become unstable (i.e. not converge). Accordingly, in this simulator, these updates are performed as follows:

- The numerical integration and the convergence calculation are performed assuming that the contact state at the $n-1$ step continues at the n th step, and the first convergent solution is obtained.
- The contact state is checked, and if the contact state at the n th step has been unchanged from that at the $n-1$ step, the procedure proceeds to the calculation at the next step ($n+1$ step).
- If the contact states at the $n-1$ step and the n th step are different, the numerical integration and convergence calculation are retried using the penalty coefficient and spring constant matching the contact state of the first convergent solution. The approximate solution obtained here is defined as the solution at the n th step, and the procedure proceeds to calculation of the next step.

4. Verification of the Contact Analysis

To verify this contact analysis method, the result by the proposed method was compared with a 2D simulation [3], which uses the difference method contact analysis based on constraint contact formulation. Since the OCL model in the 2D simulation cannot consider OCL stagger, the calculation using the proposed simulation method was also performed with the OCL stagger equal to zero. Table 1 summarizes the calculation conditions, and Fig. 6 shows a comparison of the results.

The results from the two methods do not completely match due to the differences in the OCL and pantograph models and solutions; however, since the maximum uplift value for the contact wire and the fluctuation in the low-frequency domain are equivalent, it is considered that a generally reasonable calculation is possible using the contact analysis in the proposed method.

Table 1 Calculation conditions used for the verification of the contact analysis

Span length		50 m
Number of span		6 * Total length 300 m
Type of wire	Contact wire	GT 110 mm ²
	Messenger wire	St 90 mm ²
Tension	Contact wire	9800 N
	Messenger wire	9800 N
Number of dropper		10 per a span
Contact wire deviation		0 mm
Type of dropper		Floating dropper

【Pantograph】

Type	Single arm pantograph for conventional train
Number of pantograph	1
Running speed	110 km/h

【Others】

	3D simulation	2D simulation
Time step	1 ms	16 ms
Contact lines model	Element length 0.25 m	Mass interval 0.5 m

Fig. 6 Comparison with the conventional simulator (2D): Contact wire uplift at the third supporting point

5. Calculation Example

This section describes an example of a calculation using the proposed simulation method, and the simulation results when the vehicle runs through a crossing section [9]. The calculation conditions were set as follows:

- The main track is straight, and the side track includes a curve with a radius of approximately 930 m near the branch.
- Both the main and side tracks use a simple catenary.
- Two OCL intersect at the crossing section, and an intersection is provided at approximately 120 m from the starting point of the main track.
- A spring that imitates a crossing clamp is inserted at the intersection of the contact wire with the main and side tracks to connect them.
- The contact wire of the side track is installed 60 mm above that of the main track.

Table 2 Conditions used for calculation of the crossing section

Span length		50 m
Number of span		Main track : 4 Side track : 3
Type of wire	Contact wire	PHC 110 mm ²
	Messenger wire	PH 150 mm ²
Tension	Contact wire	19800 N
	Messenger wire	19800 N
Number of dropper		10 per a span
Contact wire deviation		Less than 250 mm
Type of dropper		Floating dropper

- The Shinkansen pantograph enters the main track from the side track at 30 km/h.

Table 2 summarizes the OCL conditions, and Fig. 7 shows the static structure calculation results of OCLs and lines in the center of each track. Figure 8 shows the pantograph positions and contact points after a lapse of 1.8 seconds, 2.4 seconds, and 2.9 seconds from the start of calculation. Figure 9 shows contact points at 2.4 seconds from the start of the calculation. Figure 10 shows the waveform of the contact wire height, etc. Note that Fig. 8 schematically illustrates the movement of the pantograph as it progresses. In addition, the pantograph height in Fig.10 does not necessarily match the contact wire height, because it does not represent the contact point, but the height of the upper surface of the contact strip at the center of the panhead.

Figures 8 to 10 show that:

- The pantograph starts to make contact with the contact wire of the main track at approximately 2.3 seconds.
- The horn of the pantograph makes contact with the contact wire of the main track when the pantograph enters the crossing section.

These calculation results in consideration of the 3D placement of OCLs and the 3D shape of the pantograph as shown herein, indicate useful information to improve construction (e.g. height difference) of the crossing section and overlap. Furthermore, this type of simulation can help formulate the tolerance in height difference, in order to prevent accidents at crossing sections.

6. Conclusion

To calculate the three-dimensional dynamic behavior of OCL/pantographs, the authors developed a simulation method combining 3D pantograph models and 3D OCL models. This method can show the motion of the OCL and pantograph in crossing sections, etc., which could not be reproduced by the conventional simulations which uses two dimensional OCL model and lumped mass pantograph model.

From now on, we utilize the proposed simulation method for the detailed examination in the development of OCL and pantographs, and the investigation of accident caused on crossing section, etc.

Fig. 7 Crossing section calculation example (static structure calculation result of OCL)

Fig. 8 Contact points when passing through the crossing section

Furthermore, we aim to utilize it for more advanced maintenance management; the following are some examples of next subjects to be studied:

Fig. 9 Contact points when a pantograph contacts with both contact wire (at 2.4 seconds)

Fig. 10 Time history waveforms of height at contact point, distance between contact wire and panhead, and contact force when passing through crossing sections

- Method to construct OCL models automatically from the OCL position information obtained from equipment such as the contactless measuring device for OCL [13],
- Method for predicting contact wire wear, by importing a wear equation.

References

- [1] Aboshi, M., "Analysis for Span Cycle Motion of Catenary-Pantograph System by an Elastically Supported String Model," *Transaction of the Japan Society of Mechanical Engineers*, Series C, Vol.75, No. 755, pp.1950-1956, 2009 (in Japanese).
- [2] Bruni, S., Ambrósio, J., Carnicero, A., Cho, YH., Finner, L., Ikeda, M., Kwon, SY., Massat, JP., Stichel, S., Tur, M., and Zhang, W., "The results of the pantograph-catenary interaction benchmark," *Vehicle System Dynamics*, Vol.53, No.3, pp.412-435, 2015.
- [3] Manabe, K., Arimoto, H., "The Analysis of the Overhead Contact System by Digital Computer Simulation," *Quarterly Report of RTRI*, Vol. 12, No. 1, pp.25-

26, 1971.

- [4] Aboshi, M., "Estimation Method of Contact Line Unevenness using Dynamic Simulation," *IEEEJ Trans. IA*, Vol. 126, No. 7, pp.983-988, 2006 (in Japanese).
- [5] Ikeda, M., "'Gasen-do FE' statement of methods," *Vehicle System Dynamics*, Vol. 53, No. 3, pp.357-369, 2015.
- [6] Koyama, T., Nagao, K., Ikeda, M., "Development of Models of the Contact Lines and Pantograph for Railway Lines of Various Alignments," *RTRI Report*, Vol. 32, No. 6, pp.5-10, 2018 (in Japanese).
- [7] Koyama, T., Nagao, K., Ikeda, M., "Pantograph/Catenary Simulation Considering Static Structure Change with Temperature Shift," *RTRI Report*, Vol. 33, No. 8, pp.5-10, 2019 (in Japanese).
- [8] Nagao, K., Koyama, T., Ikeda, M., Takayuki, U., "Compliance Characteristics Analysis of Three-Dimensional Pantograph Simulation Model with Displacement Constraint of Panhead," presented at *26th J-RAIL2019*, Tokyo, Japan, Dec. 4-6, 2019 (in Japanese).
- [9] Koyama, T., Nagao, K., Ikeda, M., "Dynamic simulation of overhead contact lines and pantograph using three-dimensional MBD models," presented at *Dynamics and Design Conference 2020*, Online conference, Sep. 1-4, 2020 (in Japanese).
- [10] The Japan Society of Mechanical Engineers, "Multi-body dynamics (2) -Numerical Analysis and Applications-," Corona publishing Co. Ltd, 2007 (in Japanese).
- [11] Dassault systems, "SIMPACT," <https://www.3ds.com/products-services/simulia/products/simpack/> (Reference date: Jan. 19th, 2021).
- [12] Kajiya, H., Iida, M., Maeda, T., "Numerical Calculation of Air Flow in Underground Railway," *RTRI Report*, Vol. 7, No. 7, pp.51-58, 1993 (in Japanese).
- [13] Matsumura, I., Nezu, K., Susuki, H., Kawabata, T., Watabe, Y., "Measurement Accuracy Verification of OCL Contactless Measurement Device by On-board Test Run in Conventional Line," *RTRI Report*, Vol. 34, No. 9, pp.11-16, 2020 (in Japanese).

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