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Investigation on dynamic performance and parameter optimization design of pantograph and catenary system

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ABSTRACT

The dynamic performance of the simple catenary and the pantograph was simulated. The model of the catenary was established with the finite element method (FEM), and the pantograph was also simplified as a lumped mass model. Furthermore, based on the contact element between pantograph and catenary and the time integration method, the dynamic simulation of pantograph and catenary system was performed and the results of dynamic performance was obtained. According to the simulation results, it shows that the pantograph can run at a speed of 250 km/h and the contact loss is detected for the speed larger than 250 km/h. Subsequently the influence of the design parameters on the contact force was discussed and the optimization of the parameters was performed, the results show that the parameters, including the stiffness and damping of the pan-head and frame, the static lifted force and the tension of the contact wire, have a heavy influence on the dynamic performance of pantograph and catenary system. At last, a comparison of the contact force with the test datum is carried out, and it is showed that the agreement between the simulation results and the test datum is generally good.

1. Introduction

The pantograph moves at high speed and causes vibration in the catenary such that the contact force between pantograph and catenary varies strongly and the contact may even get lost, as shown in Fig. 1. Unfortunately, with increase in operational speeds, the influence of pantograph and catenary also increases. This may lead to a zero contact force between pantograph and catenary resulting in arcing and wear. Therefore, the research in understanding the current-collection system's dynamic characteristics and the decreasing width of dynamic vibrations are needed.

Much progress has been made to assure the current-collection quality as basic technology of a high speed railway. Ockendon and Taylor [1] described an approximate analytical formulation to determine contact force. Vinayagalingam [2] investigated the contact force variation and the pan-head trajectory using finite difference methods. Shan and Zhai [3] analyzed the catenary mode with a macroelement method. Manbe [4] studied the periodical dynamic stabilities between pantograph and catenary with discrete support springs. Wu and Brennan analyzed the effect of wave propagation in overhead wire on vibration of the pantograph and the variations of the dynamic stiffness of the catenary [5]. Arnold and Simeon [6] formulated a benchmark problem reflecting basic parts of the nonlinear dynamics of pantograph–catenary system and studied the discretization method in space and in time. Lopez-Garcia et al. [7] discussed the computation of the initial equilibrium of railway overhead based on the catenary equation. Metrikine and Bosch [8] proposed an analytical method for calculating the steady-state response of a two-level catenary to a uniformly moving pantograph. Liu et al. [9] established a vertical coupling model of the pantograph and catenary system and calculated the dynamic response by means of the mode suspension. Mei and Zhang [10] linearized the pantograph model by the Taylor series and investigated the dynamic characteristic of pantograph and catenary system with the vibration of the locomotive and track taken into consideration.

However, the researches on pantograph and catenary system mainly focus on their dynamic characteristics, such as the contact force, the lifted displacement, the material wear, etc. There have been few published articles on how to comprehensively evaluate the dynamic performances, including the dynamic strength, through finite element method and time integration method. In fact, when the steady contact between pantograph and catenary is seriously violated, the stress in the catenary may also become large and fluctuate at higher frequencies. Such a situation greatly affects the reliability of pantograph and catenary system. The objective of this research is to put forward to an accurate, fast and economical method to investigate the dynamic behavior, including the contact force, the lifted displacement and the dynamic stress and more importantly, find an optimal design of catenary and pantograph system by analyzing the influence of different design parameters on the dynamic performance under the conditions of a Chinese railway system.

The paper is organized in seven sections. Following the introduction, the finite element model of the catenary including support

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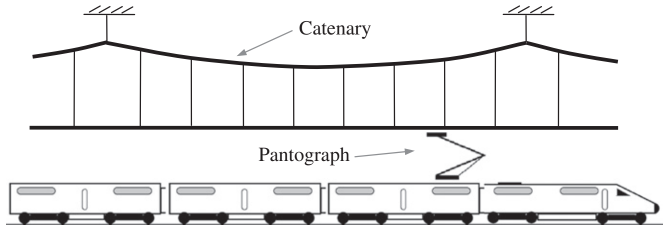

Fig. 1. Pantograph and catenary system.

wire, dropper and contact wire is detailed in Section 2. In Section 3, the pantograph is simplified as a multi-body system with mass, stiffness and damping and the dynamic model of the pantograph is described. In Section 4, based on the contact element, the coupled model of pantograph–catenary system is established and investigated. In Section 5, the simulation results of the dynamic characteristics are presented, including the contact force, the lifted displacement, the dynamic stress, etc. Moreover, the influence of the design parameters on the dynamic performance is discussed and the optimal parameters are given. Before concluding the paper, a comparison of the results of the contact force with the test datum is described in Section 6.

2. Catenary model

As shown in Fig. 2, the model of the catenary including support wire, contact wire and dropper is established for the finite element (FE) analysis. When the pantograph runs along the contact wire, the contact force between pantograph and catenary mainly produces the in-plane tension and bending deformation of the catenary. So, both the support wire and the contact wire are considered as 2D beam element. The beam element is defined by two nodes having three degrees of freedom at each node: translations in the nodal x and y directions and rotations about the nodal z-axes. However, due to relatively small linear density of the dropper compared to the others, it is modeled as a spring element. The spring element defined by two nodes has two degrees of freedom at each node: translations in the nodal x and y directions. The FE model of the catenary composed of five spans is analyzed as a whole. The number of elements used to discretize the catenary is 2744. The damping coefficient of the catenary is 0.01 N s/m^2. The parameters of material and structure of the catenary are shown in Table 1.

Therefore, the dynamic equilibrium equation of the catenary is as follows:

$$[\boldsymbol{M}_c]\{\ddot{u}_c\}+[\boldsymbol{C}_c]\{\dot{u}_c\}+[\boldsymbol{K}_c]\{\boldsymbol{u}_c\}=\{\boldsymbol{f}(\boldsymbol{t})\} \tag{1}$$

where, $[\boldsymbol{M}_c]$ is the mass matrix of the catenary; $[\boldsymbol{C}_c]$ is the damping matrix of the catenary; $[\boldsymbol{K}_c]$ is the stiffness matrix of the catenary; $\{\boldsymbol{u}_c\}$ is the nodal displacement vector of the catenary; and $\{\boldsymbol{f}(\boldsymbol{t})\}$ is the applied nodal load vector. For the dynamic equilibrium equation of the catenary mentioned above, the gravity has been taken into account.

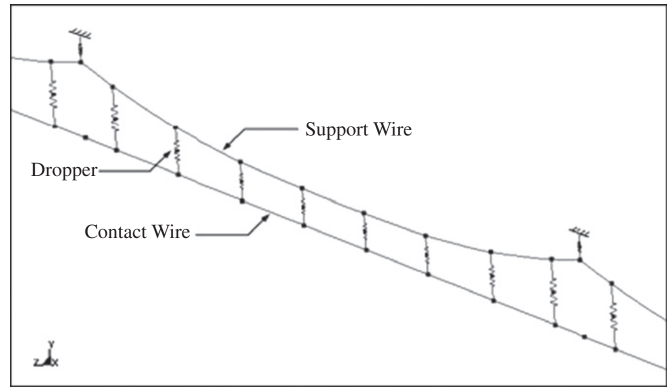

Fig. 2. Model of the catenary with one span.

3. Pantograph model

The pantograph is simplified as a spring-mass system. It consists of three lumped masses representing the pan-head (m_1), the upper frame (m_2) and the lower frame (m_3) of the pantograph. There are spring-damper elements between m_1 and m_2, between m_2 and m_3 and between m_3 and the ground, see Fig. 3. The physical parameter of the pantograph is shown as Table 2. Therefore, the dynamic equilibrium equations of the pantograph are as follows:

$$m_1\ddot{y}_1+c_1\dot{y}_1+k_1y_1-c_1\dot{y}_2-k_1y_2=-\boldsymbol{P}(\boldsymbol{t}) \tag{2}$$

$$m_2\ddot{y}_2+(c_1+c_2)\dot{y}_2+(k_1+k_2)y_2-c_2\dot{y}_3-k_2y_3-c_1\dot{y}_1-k_1y_1=0 \tag{3}$$

$$m_3\ddot{y}_3+(c_2+c_3)\dot{y}_3+(k_2+k_3)y_3-c_2\dot{y}_2-k_2y_2=\boldsymbol{F}_0 \tag{4}$$

where, $\boldsymbol{P}(\boldsymbol{t})$ is the dynamic contact force between catenary and pantograph; $\boldsymbol{F}_0$ is the static uplift force of the pantograph.

4. Pantograph–catenary coupled model

Combining the catenary model and the pantograph model, the model of pantograph–catenary system is obtained, as shown in Fig. 4. Thus, the dynamic behavior of pantograph and catenary system should satisfy Eqs. (1)–(4). In vector and matrix form, Eqs. (2)–(4) may be rewritten as Eq. (5)

$$\begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & \\ 0 & 0 & m_3 \end{bmatrix}\begin{Bmatrix} \ddot{y}_1 \\ \ddot{y}_2 \\ \ddot{y}_3 \end{Bmatrix}+\begin{bmatrix} c_1 & -c_1 & 0 \\ -c_1 & c_1+c_2 & -c_2 \\ 0 & -c_2 & c_2+c_3 \end{bmatrix}\begin{Bmatrix} \dot{y}_1 \\ \dot{y}_2 \\ \dot{y}_3 \end{Bmatrix}$$
$$+\begin{bmatrix} k_1 & -k_1 & 0 \\ -k_1 & k_1+k_2 & -k_2 \\ 0 & -k_2 & k_2+k_3 \end{bmatrix}\begin{Bmatrix} y_1 \\ y_2 \\ y_3 \end{Bmatrix}=\begin{Bmatrix} -\boldsymbol{P}(\boldsymbol{t}) \\ 0 \\ \boldsymbol{F}_0 \end{Bmatrix} \tag{5}$$

Furthermore, based on Eqs. (1) and (5), the dynamic equilibrium equation of pantograph and catenary system may be rewritten in the following general form:

$$[\boldsymbol{M}]\{\ddot{u}\}+[\boldsymbol{C}]\{\dot{u}\}+[\boldsymbol{K}]\{u\}=\{\boldsymbol{F}(\boldsymbol{t})\} \tag{6}$$

$$[\boldsymbol{M}]=\left[\begin{array}{c:ccc} \boldsymbol{M_c} & & \boldsymbol{0} & \\ \hdashline & m_1 & 0 & 0 \\ \boldsymbol{0} & 0 & m_2 & 0 \\ & 0 & 0 & m_3 \end{array}\right],\ [\boldsymbol{C}]=\left[\begin{array}{c:ccc} \boldsymbol{C_c} & & \boldsymbol{0} & \\ \hdashline & c_1 & -c_1 & 0 \\ \boldsymbol{0} & -c_1 & c_1+c_2 & -c_2 \\ & 0 & -c_2 & c_2+c_3 \end{array}\right],\ [\boldsymbol{K}]=\left[\begin{array}{c:ccc} \boldsymbol{K_c} & & \boldsymbol{0} & \\ \hdashline & k_1 & -k_1 & 0 \\ \boldsymbol{0} & -k_1 & k_1+k_2 & -k_2 \\ & 0 & -k_2 & k_2+k_3 \end{array}\right] \tag{7}$$