TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 67, Issue Special II, April, 2024

PANTOGRAPH-CATENARY DYNAMICS SIMULATION FOR HIGH-SPEED TRAINS

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Abstract: *The aim of the present paper is to simulate the pantograph-catenary dynamics for high-speed trains for the purpose of identifying the influence of various system parameters and simulation conditions on the pantograph vertical motion and on the contact force. The catenary model assumes a periodic time-variant stiffness along the span and the pantograph is modeled by a three degrees of freedom system. Simulation is made by numerically integrating the differential equations of motion using the MATLAB ODE solver. The results of the simulation reveal that the vehicle speed and the catenary stiffness - by its average value or by its degree of variation along the span - have the highest influence on the pantograph-catenary dynamic interaction.*

Key words: *high-speed train, current collection, pantograph, catenary, contact force.*

1. INTRODUCTION

High-speed rail is considered to be one of the most significant technological achievements of the second half of the last century. The development - and success - of high-speed rail have been the logical consequence of its advantages over the other modes of transport: traffic safety, high capacity, low impact on environment and passenger comfort.

High-speed train operation is, however, subject to some technical constraints, associated with phenomena that are of little importance or even negligible in vehicles traveling at conventional speeds, but which are of high intensity in the case of high-speed railway vehicles. Of these, the issues related to current collection are of the greatest importance and represent one of the blocking points regarding the increase of trains speed.

In high-speed rail transport, trains are almost exclusively electrified, the electrical energy necessary to train operation being supplied through sliding electrical contact between the pantograph placed on the top of the train and the overhead catenary contact wire.

The pantograph-catenary (PC) contact force should be kept as uniform as possible since its magnitude is highly influencing the quality of current collection. It must be neither too low to cause a loss of contact nor too high to affect pantograph and catenary reliability and to cause excessive wear. Thus, the contact force variation should be minimized.

However, a constant contact force would be achieved only in the ideal case of a catenary contact wire stiff, rectilinear, parallel to the track and also in the absence of pantograph vibrations. Actually, none of these conditions is met. The catenary stiffness varies continuously along the span, the maximum level being near the supports (masts) and the minimum level in the middle of the span. Also, the pantograph oscillates during the vehicle running and it is also affected by aerodynamic phenomena.

Under these conditions, the pantograph-catenary (PC) dynamical interaction causes important variations of the contact force, particularly at high speed. These contact force fluctuations have a negative influence on the quality of current collection and may even lead (as mentioned above) to the case where the contact between the pantograph and the catenary is lost, which represents the most unfavorable situation. In such cases electric arcs appear, resulting in negative consequences on the catenary, pantograph and train electric equipment.

Taken into account the crucial importance of ensuring a contact force within admissible limits, the dynamic interaction between the pantograph and the catenary has been a subject of study for many researchers. In an early notable paper on this topic of Wu and Brennan, the pantograph-catenary interaction is studied on the basis of a single degree of freedom (DOF) time-varying system [1]. The dynamic behavior and the stability of the system are investigated on this simple model. Subsequent research on this topic has focused mainly on developing more precise models of pantograph and catenary and on simulating as accurately as possible their mutual interaction. In all cases, the pantograph is modelled as a lumped mass model with one [1] two [2,3,4,5] or three DOF [3,6,7,8,9].

Regarding the catenary, the main challenge for the researchers is to develop models to reflect as accurately as possible the time variations of its mechanical parameters (along the span). To achieve this, two types of methods are widely used: finite element method [2,3,6,9,10] and approximation using harmonic functions (Fourier series) [10,11,12]. In [7] the analysis includes in the model the reduced mass of the catenary. Kobayasi et al. [4] make a comparison between the catenary-pantograph interaction simulation results and those obtained by running tests, while in [13] the pantograph-catenary interaction is investigated through simulations using MSC.ADAMS and ANSYS software. The results of a benchmark regarding the simulation of PC interaction, with the purpose of evaluating the dispersion of the results obtained by different simulation models and methodologies are presented in ref. [14].

Given the need of keeping the PC contact force values within a limited range, there is an increasing interest for the active control of pantograph vibrations [2,3,7,11,12], the key issues in this field being the control strategy, the actuator position and the contact force estimation.

The norms and regulations in the railway field specify the criteria for the evaluation of the quality of the contact as a result of the PC interaction. These criteria indicate the admissible values of the static contact force, its standard deviation, the minimum and maximum permissible dynamic contact force, the maximum vertical amplitude of the pantograph displacement, the maximum uplift of the contact wire near the supports, and the permissible arcing rate, expressed as a percentage of time. It can be seen that these criteria are connected to the pantograph displacement and particularly to the contact force. It is included here also the arching rate criterion since electric arc corresponds to the case of a null contact force.

Considering the above-mentioned criteria, the aim of the present work is to evaluate, using numerical simulations, the influence of various parameters on the dynamics of PC system, of interest being the pantograph head vertical displacement and the contact force.

2. MODELLING OF THE PANTOGRAPH-CATENARY SYSTEM

2.1 Modelling of the catenary

A railway catenary is a periodic structure with the purpose of supplying electrical energy to trains. Some typical high-speed catenary systems in Japan, France and Germany are shown in fig.1[15].

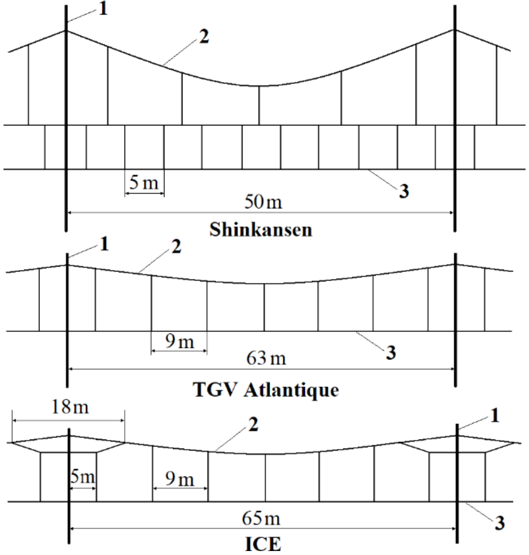

Fig.1. High-speed catenary systems

The catenary system includes masts (1), which are supporting the messenger (carrier) wire (2) to which the contact wire (3) is attached by droppers. Both wires are tensioned to reduce bending.

The periodicity of the catenary is given by masts, the variation of the contact wire stiffness being similar along each span between the pillars, the overhead wire static stiffness fluctuating from a maximum value near the masts to a minimum one in the middle of the span. The time-variant stiffness *k(t)* along the span can be written according to the model proposed by Wu and Brennan [1]:

$$k(t) = k_m + k_d \cos 2\pi \frac{x}{L} = k_m + k_d \cos 2\pi \frac{v}{L} t \text{, (1)}$$

where x is the pantograph position (distance from the mast), L the span length (distance between masts), v the train speed and

$$k_m = \frac{k_{\max} + k_{\min}}{2} \quad (2)$$

$$k_d = \frac{k_{\max} - k_{\min}}{2} \quad (3)$$

k_{max} and k_{min} being, respectively, the maximum and the minimum stiffness in the span. The ratio between the amplitude of the stiffness variation k_d and the average stiffness k_m

$$\varepsilon = \frac{k_d}{k_m} \quad (4)$$

reflects the variation of stiffness along a span.

Using (4), equation (1) can be written as

$$k(t) = k_m \left(1 + \varepsilon \cos 2\pi \frac{v}{L} t\right) = k_m \left(1 + \varepsilon \cos \omega t\right) \text{(5)}$$

which represents the periodic variation of the stiffness of the catenary.

2.2 Modelling of the pantograph

The pantograph is an equipment located on the roof of the railway motor electric vehicle in order to collect power from the overhead catenary. There are many types of pantographs, depending on the speed of operation, shape, type of electric current, lifting devices, etc.

Since the simulation of PC dynamics for high-speed trains is addressed in the present work, a pantograph with appropriate features is considered.

A typical pantograph for high-speed trains can be seen in fig. 2 [16].

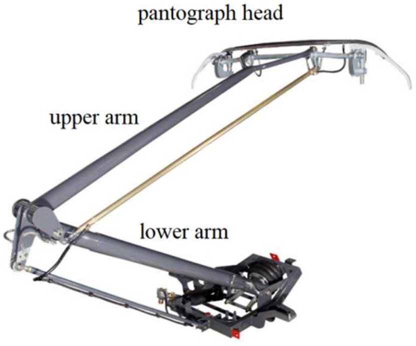

Fig.2. High-speed Faiveley pantograph [16].

The pantograph model (see fig.3) is a three degrees of freedom system, including pantograph's lumped masses - the equivalent masses in vertical translation of pantograph head, upper and lower arm - and Kelvin-Voight models to consider system stiffness and damping.

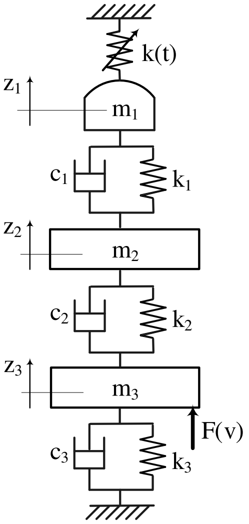

Fig.3. The catenary-pantograph model.

The model in fig. 3 also includes the static contact force *F(v)*, i.e., the vertical force that the pantograph exerts on the catenary, which is given by:

$$F(v) = F_S + \alpha v^2 . \qquad (6)$$

The force in equation (6) has two components, the force F_S produced by the pantograph lifting device and the aerodynamic uplift force which depends on the square of the speed by the aerodynamic coefficient α.

The model also includes the catenary variable stiffness *k(t)* given by equation (5).

The equations of motion for the above-presented model are:

$$\begin{aligned} m_1\ddot{z}_1 + c_1(\dot{z}_1 - \dot{z}_2) + k_1(z_1 - z_2) + k(t)z_1 &= 0 \\ m_2\ddot{z}_2 + c_1(\dot{z}_2 - \dot{z}_1) + c_2(\dot{z}_2 - \dot{z}_3) + & \\ + k_1(z_2 - z_1) + k_2(z_2 - z_3) &= 0 \\ m_3\ddot{z}_3 + c_2(\dot{z}_3 - \dot{z}_2) + c_3\dot{z}_3 + k_2(z_3 - z_2) + & \\ + k_3 z_3 &= F(v) \qquad (7) \end{aligned}$$

Equations (7) are the basis for the simulation of the PC dynamic interaction.

3. RESULTS AND DISCUSSION

In this section are presented the results of the numerical integration of differential equations system (7) using the MATLAB *ODE* solver. The parameter basic values used in the numerical simulation are: $m_1 = 7.5$ kg; $m_2 = 4.6$ kg $m_3 = 4.8$ kg; $k_1 = 6000$ N/m; $k_2 = 5400$ N/m; $k_3 = 1$ N/m; $c_1 = 10$ Ns/m; $c_2 = 5$ Ns/m; $c_3 = 32$ Ns/m; $\alpha = 0.00097$ Nh^2/km^2; $k_m = 4000$ N/m; $\varepsilon = 0.4$; L=50 m.

Since the influence of different parameters on the PC dynamic interaction will be investigated, some alternative values than the reference ones will also be considered.

The simulation was done for a period of 12 seconds; however, the results will be presented only for the time required to cover 100 meters, distance equivalent to two spans, the 11th and the 12th (between 500 and 600 meters traveled).

In the simulation is investigated the influence of different system parameters and simulation conditions on the pantograph head vertical displacement and on the contact force, the latter being given by:

$$F_C(t) = k_c(t) z_1 . \qquad (8)$$

In fig. 4 and 5 is shown the influence of train speed on the pantograph head vertical displacement and pantograph-catenary contact force, respectively. It is to be noted that in both cases this influence is very important, an increased train speed leading to larger amplitudes of pantograph motion and contact forces.

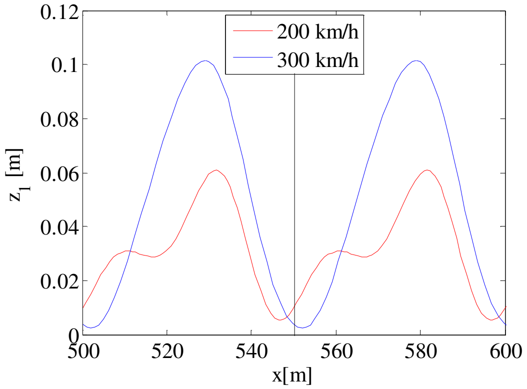

Fig.4. Influence of speed on the pantograph head displacement.

This confirms that the issue of current collection has a special importance in the case of high-speed rail transportation.

It can be observed, especially at higher speed, the effect of the reduced catenary stiffness in the middle of the span, maximum values of displacement and contact force being reached in this area.

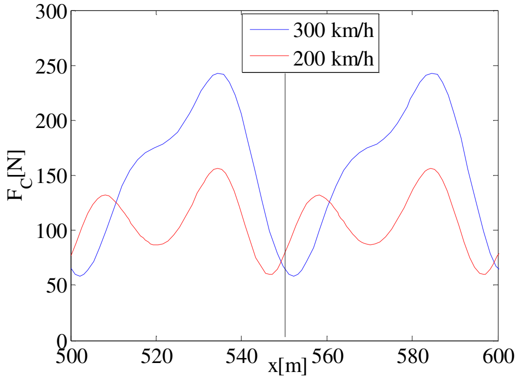

Fig.5. Influence of speed on the PC contact force.

Apart from the train speed, the influence of some of the parameters of the PC system on its dynamics is of interest. For this reason, in the following are presented the results of the simulations performed for a train speed of 300 km/h, trying to highlight the influence of each parameter separately.

Fig. 6 and 7 highlight the influence of the stiffness variation along a span (quantified by the coefficient ε) on the pantograph head vertical displacement and pantograph-catenary contact force, respectively.

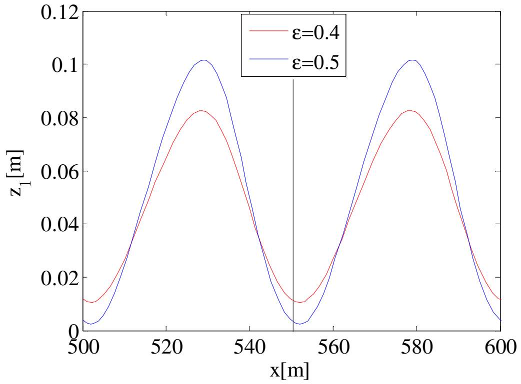

Fig.6. Influence of stiffness variation on the pantograph head displacement.

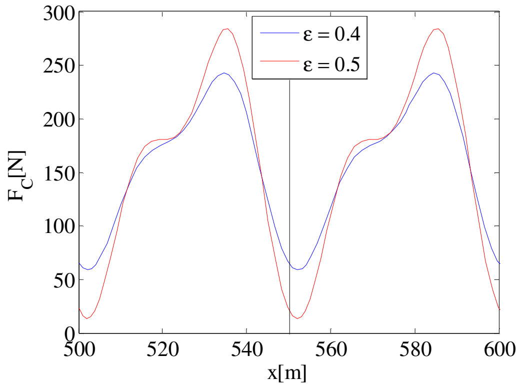

Fig.7. Influence of stiffness variation on the PC contact force.

It is very clear that that a lower fluctuation of the catenary stiffness (thus a lower value of ε) has an important positive effect of reducing the amplitudes of both the pantograph vertical displacement and the contact force. The reduction of the amplitudes is the result of both the increase of the minimum levels and the decrease of the maximum levels of the vertical displacement and contact force. A relatively similar effect has the average stiffness k_m (see fig. 8 and 9). An increased catenary static stiffness (which, for ε constant, is given a by larger catenary average stiffness) has the same beneficial effect of reducing the vertical displacement of the pantograph and the PC contact force.

A larger catenary stiffness has a higher influence on the vertical displacement in the area around the middle of the span (see fig. 8), while in the case of the contact force the effect of reduction is more uniform along the span (see fig.9).

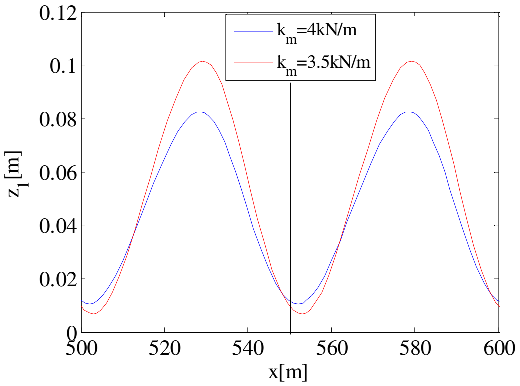

Fig.8. Influence of the catenary average stiffness on the pantograph head displacement.

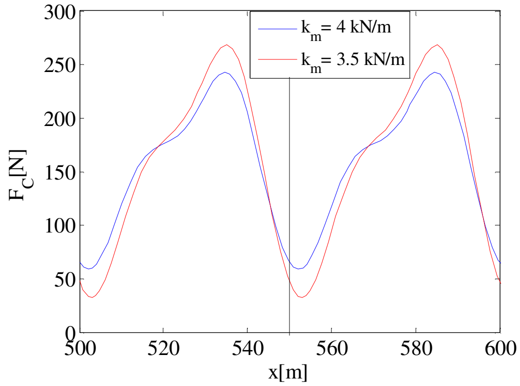

Fig.9. Influence of the catenary average stiffness on the PC contact force.

Regarding the pantograph, it is of interest to analyze the influence of the parameters related to its upper part, that comes into contact with the catenary.

The influence of pantograph upper part mass on the pantograph head vertical displacement and PC contact force is presented in fig. 10 and 11, respectively. It can be seen that a reduction of the mass has, as expected (since the inertia is reduced), an improvement in terms of pantograph vertical motion and contact force.

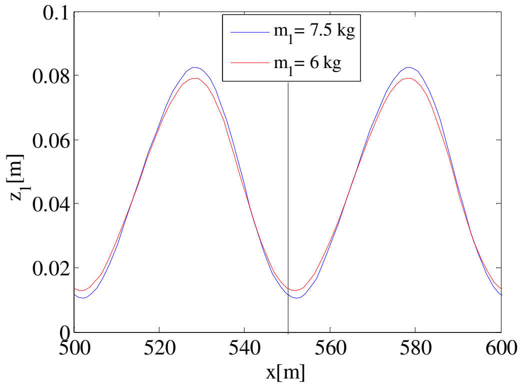

Fig.10. Influence of the pantograph mass on the pantograph head displacement.

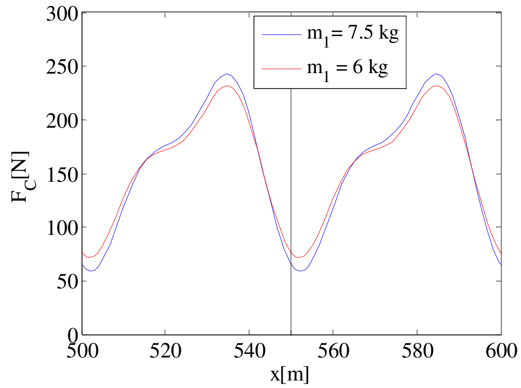

Fig.11. Influence of the pantograph mass on the PC contact force.

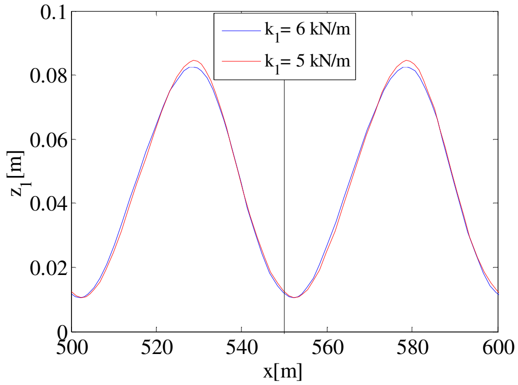

Fig.12. Influence of the pantograph stiffness on the pantograph head displacement.

As in the case of the catenary stiffness influence, the reduction of the amplitudes is done both by the increase of the minimum level (of displacement or contact force) and the decrease of the maximum one. It can be observed that the effect of mass is less important than that of stiffness, either by its average value or by its degree of variation along the span.

Less obvious is the case of the influence of the pantograph suspension stiffness, which is shown in fig. 12 (regarding the pantograph displacement) and fig. 13 (regarding the pantograph-catenary contact force).

An increased stiffness has some positive effect on both pantograph motion and PC contact force, but the effect is not important.

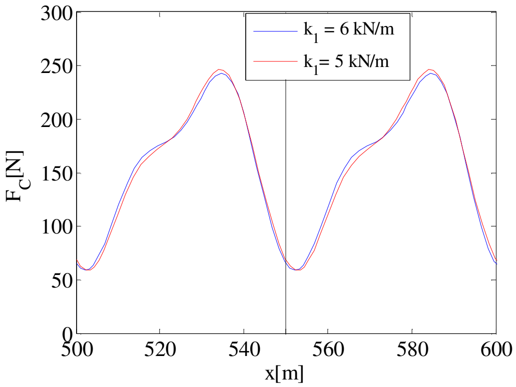

Fig.13. Influence of the pantograph stiffness on the PC contact force.

4. CONCLUSION

Current collection is one of the critical technical constraints of high-speed rail transport. The PC dynamical interaction at high-speed causes important variations of the contact force, which affects the quality of the current collection and may lead to the loss of contact between pantograph and catenary.

The aim of the present paper was to simulate the PC dynamics with the purpose of identifying the influence of various system parameters and simulation conditions on the pantograph head vertical displacement and on the contact force.

The catenary model assumed a periodic time-variant stiffness along the span between the pillars. The adopted pantograph model was a three degrees of freedom system including lumped masses, stiffness and damping, and also considered the aerodynamic uplift force.

First of all, it should be emphasized that the numerical results for the contact force and the pantograph head vertical displacement are consistent with those of the state of the art in the field of pantograph-catenary interaction. The results are also in accordance with the European standard EN 50367 (“Railway applications - Fixed installations and rolling stock - Criteria to achieve technical compatibility between pantographs and overhead contact line"). According to this norm, the maximum contact force is 300 N for speeds lower than 200 km/h and 350 N for speeds higher than 200 km/h.

The analysis confirmed that the vehicle speed has the most important impact on the amplitudes of pantograph vertical motion and pantograph-catenary contact forces, higher speed leading to significant increases in their magnitude.

Of the system parameters, the simulation revealed that the catenary stiffness has the highest influence on the PC dynamic interaction. A lower fluctuation of the catenary stiffness along the span or/and a higher catenary average stiffness has/have an important positive effect of reducing the amplitudes of both the pantograph vertical displacement and the contact force.

Pantograph parameters proved to have less impact on the PC dynamic interaction. The reduction of the pantograph upper part mass proved to have a positive effect, on the other hand pantograph suspension stiffness modification did not show a significant influence.

It can be concluded that to keep the pantograph vertical displacement and PC contact force within the admissible limits in the high-speed domain, the catenary stiffness must be increased and its variation along the span must be reduced. Regarding the pantograph, the best action to be taken proved to be the reduction of the mass in direct contact with the catenary contact wire.

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Simularea dinamicii sistemului pantograf-catenară în cazul trenurilor de mare viteză

Scopul prezentei lucrări este de a realiza o simulare a dinamicii sistemului pantograf-catenară pentru trenuri de mare viteză, pentru a identifica influența diferiților parametri ai sistemului și a condițiilor de circulație asupra deplasării verticale a pantografului și asupra forței de contact. Modelul catenarei presupune o rigiditate periodică variabilă în timp de-a lungul deschiderii, iar pantograful este modelat printr-un sistem de trei grade de libertate. Simularea se face prin integrarea numerică a ecuațiilor diferențiale de mișcare folosind solver-ul MATLAB ODE. Rezultatele simulării arată că viteza vehiculului și rigiditatea catenarei - prin valoarea sa medie sau prin gradul său de variație de-a lungul deschiderii - au cea mai mare influență asupra interacțiunii dinamice pantograf-catenară.

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