



High speed railways: pantograph and overhead lines modelling and simulation

G. Diana, S. Bruni, A. Collina, F. Fossati, F. Resta
*Politecnico di Milano, Department of Mech. Eng.,
P.zza L. da Vinci 32, 20133, Milano, Italy,
Email: Stefano.Bruni@polimi.it*

Abstract

The paper describes some aspects of the researches carried out on the subject of pantograph-catenary interaction at the Department of Mech. Eng. of Politecnico di Milano. In particular a mathematical model of pantograph and overhead equipment dynamic interaction has been developed, and validated by means of comparison with experimental results. The model has been used for the design of the italian high speed line, and for preliminary studies on the subject of active controlled pantograph.

1. Introduction

Current collection from overhead catenary represents one of the major problems related to the development of high speed rail systems. This task is performed by means of one or more collector strips mounted on a pantograph. As the speed of the train increases over 180-200 km/h, the dynamics of the coupled system pantograph-overhead equipment (OHE) plays a fundamental role in the quality of the current collection: it follows that static criteria are not suitable for the design of high speed catenary and pantograph. As an example, the adoption of a stitch catenary, equipped with "Y" suspension, or the adoption of the contact wire pre-sag, depend on quasi-static considerations. Their use tends to be abandoned on new design catenaries, [1], [2], since their effectiveness tends to be of less importance at high speed.

The study of the dynamic interaction between pantograph and OHE can be performed by means of mathematical models [6]: in the last decade, several computer codes have been developed by railway

companies ([3]), university research centres ([2] and [5]), and pantograph manufacturers ([4]).

A simulation program can be used for the optimisation (in the design stage) and final verification of new OHEs and pantographs, for the evaluation of service interoperability and for evaluating the performances of active controlled pantographs. This last topic is related to service interoperability: active control can help to optimise pantograph performance with respect to different catenaries.

Pantograph-OHE dynamic interaction is one of the research fields developed at Politecnico di Milano, Department of Mechanical Engineering, including mathematical modelling, laboratory and on-line tests. A mathematical model has been improved and validated taking advantage from laboratory test on pantographs and droppers, and on-line tests on high speed and ordinary lines. The development of the simulation code has been carried out in co-operation with Italferr (engineering company of Italian State railway F.S.) and ABB-SAE Sadelmi (OHE manufacturer). More recently researches have also been conducted on the topic of active controlled pantograph [9], aimed to investigating on different control strategies and their applicability. The paper describes the main results and the guidelines of future researches of research in the area of mathematical modelling and control.

2. The mathematical model

The mathematical model of pantograph-OHE dynamic interaction here described has been developed mainly for catenary design and verification, and takes into account for:

- catenary geometry (dropper location, double/single contact wire);
- flexural stiffness of the contact wire, particularly important in correspondence of the singular points (dropper and registration arms);
- non linear behaviour of the droppers, due to slackening, which is essential for a realistic simulation of the contact force.

A finite element schematisation of the catenary is adopted, while dropper's behaviour is included by means of non linear forces, function of catenary motion. Pantograph behaviour is reproduced with a lumped parameters model, which has proved to be adequate up to 30 Hz.

2.1 Mathematical model of the catenary

The OHE schematisation can be restricted to the vertical plane, or extended in 3-D, if the *zig-zag* location of the contact wire is needed in

the analysis. Bernoulli-Euler 2-node tensioned beam element are adopted for contact wire, messenger wire, and auxiliary wires, if present: the adopted length of each element is 1÷1.5m. Boundary conditions are set up by means of springs, as well as for supports at each span, while registration arm is reproduced with a lumped mass. A typical number of span ranges from 6 to 10. The equations of motion are written through a lagrangian approach, around the static equilibrium position:

$$[M_c] \ddot{\underline{x}}_c + [R_{pp}] \dot{\underline{x}}_c + [K_{pp}] \underline{x}_c = \underline{F}_{cc}(\dot{\underline{x}}_c, \underline{x}_c) + \underline{F}_{cp}(\ddot{\underline{x}}_c, \dot{\underline{x}}_c, \underline{x}_c, \dot{\underline{x}}_p, \underline{x}_p) \quad (1)$$

where \underline{x}_c collects the d.o.f of the catenary, $[M_c]$, $[R_c]$ and $[K_c]$ are respectively mass, damping and stiffness matrices, being $[R_c]=\alpha[M_c]+\beta[K_c]$. The term \underline{F}_{cc} and \underline{F}_{cp} are respectively the generalised force vectors related to the contact force exchanged between pantograph and contact wire and to the non linear droppers' behaviour. Non linearity due to droppers can be included directly by means of the relationship between force and relative displacement obtained from laboratory tests, or by means of equivalent mechanical models, used for special kind of dropper [10] which exhibits a hysteretic behaviour.

2.2 Mathematical model of the pantograph

A lumped parameters scheme of the pantograph is adopted, based on a linear representation of the pantograph, in the neighbourhood of its working position. More sophisticated models can be adopted if the investigation involves a frequency range wider than 0-30 Hz. In this case the key element is model of the collector head, whose flexural resonances have to be taken into account, with a f.e.m. model or with a modal

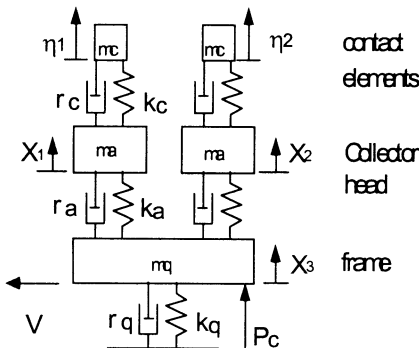


Figure 1 Lumped parameters model of the pantograph

approach. Moreover, a full f.e.m. schematisation of the entire pantograph is required only if the stress in pantograph members are needed. The lumped parameters schematisation, shown in Figure 1 for the ATR90 pantograph.

Besides the d.o.f. representing the two collector heads and the frame motion, two supplementary d.o.f. related to the point of contact are included (figure 1).

The equations of motion of the pantograph are the following:



850 Computers in Railways

$$\left[\mathbf{M}_p \right] \begin{Bmatrix} \ddot{\underline{x}}_p \\ \ddot{\underline{\eta}} \end{Bmatrix} + \left[\mathbf{R}_p \right] \begin{Bmatrix} \dot{\underline{x}}_p \\ \dot{\underline{\eta}} \end{Bmatrix} + \left[\mathbf{K}_p \right] \begin{Bmatrix} \underline{x}_p \\ \underline{\eta} \end{Bmatrix} = \begin{Bmatrix} \underline{F}_p \\ \underline{F}_\eta \end{Bmatrix} \quad \underline{F}_p = \begin{Bmatrix} 0 \\ 0 \\ P_c \end{Bmatrix} ; \quad \underline{F}_\eta = \begin{Bmatrix} F_{c1} \\ F_{c2} \end{Bmatrix} \quad (2)$$

where \underline{x}_p collect the d.o.f. of the pantograph, and η the d.o.f. of the contact points, which follow the motion of the contact wire.

2.3 Model of pantograph-OHE interaction

The partitioning of eq (2), leads to the following equation, where the first one refers to the motion of the pantograph d.o.f., and the second one is used for the calculation of the contact force:

$$\begin{cases} \left[\mathbf{M}_{pp} \right] \ddot{\underline{x}}_p + \left[\mathbf{R}_{pp} \right] \dot{\underline{x}}_p + \left[\mathbf{K}_{pp} \right] \underline{x}_p = - \left[\mathbf{R}_{p\eta} \right] \dot{\underline{\eta}} - \left[\mathbf{K}_{p\eta} \right] \underline{\eta} + \underline{F}_p \\ \left[\mathbf{M}_{\eta\eta} \right] \ddot{\underline{\eta}} + \left[\mathbf{R}_{\eta\eta} \right] \dot{\underline{\eta}} + \left[\mathbf{K}_{\eta\eta} \right] \underline{\eta} + \left[\mathbf{R}_{\eta p} \right] \dot{\underline{x}}_p + \left[\mathbf{K}_{\eta p} \right] \underline{x}_p = \underline{F}_\eta \end{cases} \quad (3)$$

The motion of each contact point is a function of catenary motion, and of the location ξ of the collector head along the k-th finite element of the contact wire. In particular, in the vertical plane, the motion of the contact point moving in longitudinal direction with a speed V , is expressed through the shape function of the finite element:

$$\eta_i = \underline{f}(\xi)^T \underline{x}_k ; \quad \dot{\eta}_i = \underline{f}(\xi)^T \dot{\underline{x}}_k + V \frac{\partial \underline{f}^T}{\partial \xi} \Big|_{\xi} \underline{x}_k ; \quad \ddot{\eta}_i = \underline{f}(\xi)^T \ddot{\underline{x}}_k + 2V \frac{\partial \underline{f}^T}{\partial \xi} \Big|_{\xi} \dot{\underline{x}}_k + V^2 \frac{\partial^2 \underline{f}^T}{\partial \xi^2} \Big|_{\xi} \underline{x}_k \quad (4)$$

being \underline{x}_k the vector of the nodal d.o.f. of the k-th finite element. Inserting eq.(4) into the first of eq.(3), the generalised forces acting on the pantograph can be expressed as a function of catenary motion, while from the second of eq.(3), the contact forces are expressed as a function of both pantograph and catenary motion. Finally, nodal forces on the catenary, corresponding to the contact forces \underline{F}_η applied to the k-th finite element at the contact wire are calculated through the shape function of the finite element. Putting together eqs.(1), (3) and (4), the following set of equations of motion are obtained for the catenary and the pantograph. The forcing terms \underline{F}_{cp} and \underline{F}_{pc} act as coupling terms between the two sets of equations and therefore include in the model the effects of pantograph-OHE interaction:

$$\begin{cases} \left[\mathbf{M}_c \right] \ddot{\underline{x}}_c + \left[\mathbf{R}_{pp} \right] \dot{\underline{x}}_c + \left[\mathbf{K}_{pp} \right] \underline{x}_c = \underline{F}_{cc}(\underline{\dot{x}}_c, \underline{x}_c) + \underline{F}_{cp}(\ddot{\underline{x}}_p, \dot{\underline{x}}_p, \underline{x}_p, \dot{\underline{x}}_c, \underline{x}_c) \\ \left[\mathbf{M}_{pp} \right] \ddot{\underline{x}}_p + \left[\mathbf{R}_{pp} \right] \dot{\underline{x}}_p + \left[\mathbf{K}_{pp} \right] \underline{x}_p = \underline{F}_p + \underline{F}_{pc}(\ddot{\underline{x}}_c, \dot{\underline{x}}_c, \underline{x}_c) \end{cases} \quad (5)$$

The equations of motion are integrated in the time domain, by means of

an iterative procedure [7].

3. Comparison with experimental results

Results of experimental on-line tests have been used in order to obtain a validation of the mathematical model. In this section, some comparisons between numerical results and measurements carried out in 1996 on the the FS line "Direttissima" connecting Florence to Rome will be presented. Tests have been carried out at different train speeds, ranging from 150 to 280km/h, with an instrumented ETR500 test train, which let also the measurements of contact force, performed by FS.

As a first example, the time history of the vertical displacement of the contact wire at the suspension, is shown in figure 2. The two maximum values correspond to the transit of the first pantograph (129N preload) and the second one (210N preload)..

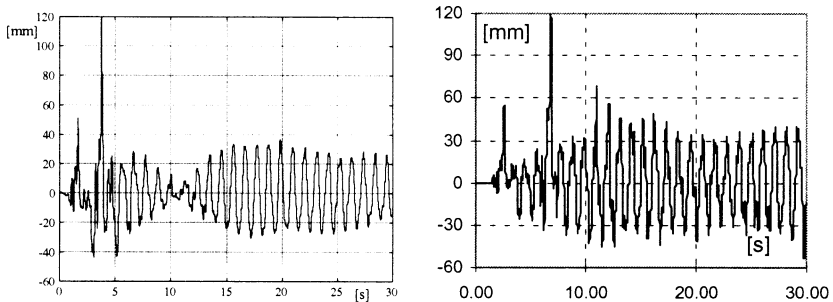


Figure 2: Vertical displacement of contact wire under suspension: left (a), measurement, right (b), simulation.

As an example of parametric investigation, the influence of the droppers on contact force is studied: Figure 3 show the measured contact force of the second pantograph, and refers to a section of the line equipped the with single wire droppers (left), and with prototypes of elastic droppers (right); for this second case, a better current collection quality is revealed by the lower dynamic variation of the contact force. The corresponding results obtained from the simulation, presented in fig.4a (single wire droppers) and fig.4b (prototype droppers), show the same tendency as the experimental ones. The simulation model is able to show the influence of parameter variation, and therefore is a reliable aid for catenary design.

852 Computers in Railways

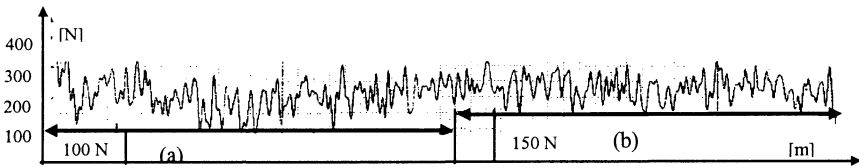


Figure 3. Contact force of second pantograph: on board measurements : (a) single wire dropper, (b) ring elastic dropper. (from [wccr]).

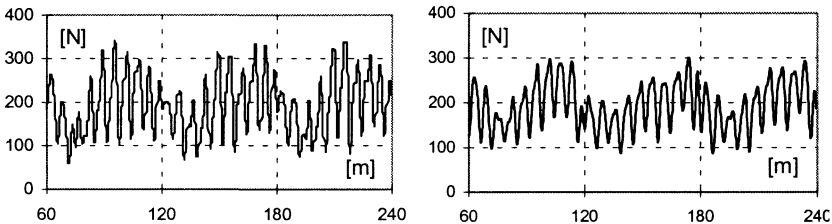


Figure 4 Contact force simulation of second pantograph: (left) single wire dropper, (right) ring elastic dropper.

4. Active control of the pantograph

In the following a brief description of the basic ideas of the proposed active control strategies and some results will be reported; in particular these active control structures have been numerically tested by means of the above mentioned numerical model of the pantograph + catenary interaction. Basically the control strategy for both single and double pantographs configurations is based on the feedback of the difference between the contact force and a reference value.

The proposed control strategy is based on a Extended Kalman Filter (EKF) in order to have a real-time estimation technique for the contact force evaluation, instead of measuring it.

Different control methodologies (like PD regulators and Optimal Control strategies) have been tested [8].; in the following only Proportional Derivative application will be shown. Moreover, two different solutions have been checked: the first one deals with applying the control force to the pantograph base frame while, in the second one, the control force has been directly applied to the collector head [8]. In the present paper only the head actuated pantograph will be considered.

4.1 Contact force estimation

In order to guarantee the practical feasibility of the above-mentioned control strategy, only on-line pantograph displacement measurements are

supposed available to controller, neglecting any overhead line measured data or contact force measurements. More in details the contact force is evaluated by means of the EKF [8].

As well known, EKF technique needs a reference model of the system: in the present work two different reference models have been considered based on a discrete 2 d.o.f. pantograph reference model (“Ref. Model 1”) and a mixed catenary + pantograph reference model (“Ref. Model 2”).

The “Ref. Model 1” is a 2 d.o.f. system, which respectively represent the collector head and base frame pantograph displacements; this model is able to reproduce only the first two rigid pantograph vibration modes and has been used in order to estimate the contact force by means of the EKF.

As an example, figure 5 shows a comparison between the contact force time history numerically simulated by means of the complete model and the estimated contact force, carried out observing pantograph displacements only.

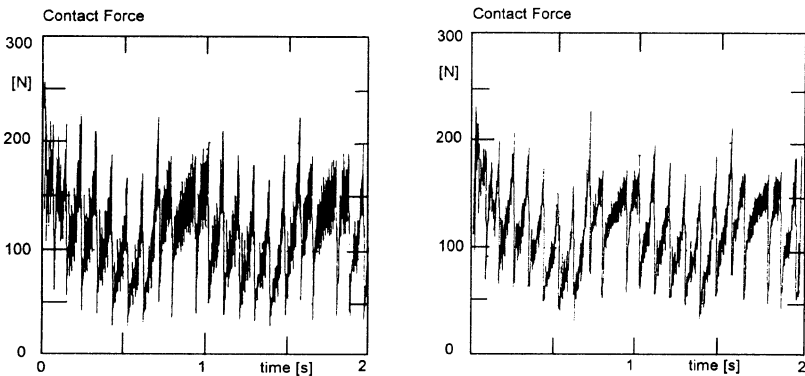


Figure 5: Time history of the contact force at 250[km/h]. (a) Simulated; (b) Estimated results using EKF based on the Reference Model 1

The EKF performance using the Reference Model 1 are quite good at the lowest frequencies, while at the higher frequencies (10hz or more) a time delay between simulated and estimated force has been introduced.

In order to improve the estimation procedure performance, a different reference model based on a modal approach to define the overhead line behaviour has been set-up (in the following named “Ref. Model 2”).

The catenary mass and stiffness properties are reproduced by means of a tensioned beam and the mast stiffness by means of springs placed between the adjoining spans. The pantograph model is based on a two degrees of freedom system and the collector head is supposed to be always in contact with the overhead line.

854 Computers in Railways

Also in this case, the contact force F_c has been included in the Ref. Model 2 extended state vector, which contains the base frame pantograph displacement and velocity and the modal co-ordinates describing the overhead line dynamics.

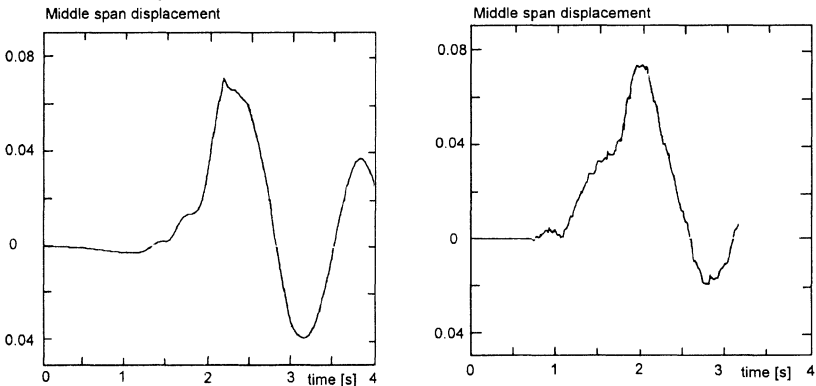


Figure 6: Time history of the contact wire middle span displacement at 250[km/h]. (a) Simulated. (b) Estimated results

Ref. Model 2 reveals more effective than the Ref. Model 1 in terms of contact force phase lag introduced by the filtering effect; the better contact force estimation allows to improve the controller parameters in order to reach better performance of the overall system. Moreover using the Ref. Model 2, it is possible to have some information on the catenary motion too. As an example in figure 6 the middle span displacement time history due to pantograph passage obtained by means of the complete numerical Mmodel and the estimated ones obtained by means of the Ref. Model 2 are reported.

4.2 Some results

The control strategy based on the force control loop and on the contact force estimation using the EKF method have been checked by means of the complete numerical model described in section 2.

As far as the Ref. Model 1 is concerned, the above mentioned time delay introduced in contact force estimation allows to control only the low-frequency dynamics of the pantograph, up to the frequencies related to span passage, while no decrease of the spectral component of contact force relevant to droppers passage frequency (10.5Hz) is obtained.

Table I reports the contact force spectrum components for the actuated pantograph using the contact force estimation carried out by means of the Ref. Model 2 in comparison with the uncontrolled and the controlled with

the estimation using the Ref. Model 1. The better results are due to the reference model capabilities: the Ref. Model 2 allows to reduce the estimated contact force phase lag at the higher frequencies (20 Hz): this lead to a better contact force estimation, improving controller action and performance of the whole system.

Frequency	No control	Active Pant. Ref. Mod. 1	Active Pant. Ref. Mod. 2
Span Passage (1.15Hz)	20 N	7 N	8 N
Droppers passage (10.5Hz)	22 N	19 N	13 N
2xDroppers Passage (21 Hz)	16 N	16 N	11 N

Table I: Spectral components of contact forces

5. Use of the simulation for diagnostic purposes

The above mentioned contact force estimation procedure, based on the Extended Kalman Filter, used for the pantograph active control purposes seems to be very interesting also for overhead line diagnostics problems. Basically the main idea is to use the pantograph measures, already available for active control purposes, in order to estimate the contact force (fig.5) and catenary dynamics (fig.6), obtaining some information relevant to overhead line conditions too, for diagnostics and maintenance. More in details, it is possible to assess the overhead line status by means of some typical parameters related to contact line wear, droppers failure, suspension set devices failure, contact line tension variation and so on: meaningful catenary parameters trend analysis could be carried out by means of the previously described estimation technique.

Following this approach in principle allows to obtain catenary dynamics information using pantograph collector head and base frame displacements only; by this way no overhead line measurements are necessary with great maintenance cost advantages.

6. Concluding remarks

A reliable mathematical model of pantograph-catenary dynamic interaction is a useful tool in the design stage of the catenary, letting the selection of the optimal solution, and consequently reducing the cost and duration of on-line tests.

The results of the simulation can also be adopted for the early development of active control for pantograph, i.e. selection of control



strategy and evaluation of its performance.

The simulation model has the potentialities of being adopted also for diagnostics and maintenance purposes, such as the evaluation of medium wear rate of the contact wire. The last topic could be of great importance in view of a modern approach to OHE maintenance.

References

- [1] Descourbes M., 10 ans de progres: la catenaire, *RVGCF*, N.10, octobre, 1991.
- [2] G. Diana, M. Falco, S. Fasciolo, V. Morelli, Experimental and numerical investigation on the dynamic behaviour of the catenary for AV italian railway line, WCRR '97, Nov. 1998, Florence, Italy.
- [3] G. A. Scott, M. Cook, Extending the limits of pantograph overhead line performance, *IMechE*, C514/053.
- [4] Brodkorb A., Semrau M., Simulationsmodell des Systems Oberleitungskettenwerk und Stromabnehmer, *Elektrische Bahnen*, N.91, pp.105-113, 1993.
- [5] Nowak B., Link M., Zur Optimierung der dynamischen Parameter des ICE-Stromabnehmers durch Simulation der Fahrdynamik, *VDI Berichte* 635, pp. 147-166, 1987.
- [6] Poetsch G. et al, Pantograph/Catenary Dynamics and Control, *Vehicle System Dynamics*, Vol. 28, N2-3, Swets & Zeitlinger Publishers, pp. 159-195, August 1998.
- [7] Diana G., et al. Research on the dynamic behaviour of the pantograph-catenary system, Internal Report of Politecnico di Milano, Department of Mechanics, Milano, October 1988 (in italian)
- [8] G. Diana, F. Fossati, F. Resta, A. Collina, Active control of high speed train pantograph. IIIrd Int. Conf. on Motion and Vibr. Control, Chiba, 1-6 sept., 1996, Japan.
- [9] G. Diana, F. Fossati, F. Resta, High speed railway: collecting pantographs active control and overhead lines diagnostic solutions, on publication on *Vehicle System Dynamics*, Swets & Zeitlinger Publishers
- [10] M. Boccione et al., New catenary components tested for the AV italian railway line: damped elastic droppers, World Rail Congress, WCRR '97, 16-19 Nov, 1998, Florence, Italy.