Development of Multibody Pantograph and Finite Element Catenary Models for Application to High-speed Railway Operations

EXTENDED ABSTRACT

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Abstract

High-speed railway overhead systems are subjected to tight functional requirements to deliver electrical energy to train’s engines, in order to ensure their reliability and to control their maintenance periods. The quest for interoperability of different pantographs, in existing and projected catenary systems, puts an extra demand on the ability to control their dynamic behaviour. The quality of the current collection is of fundamental importance as the loss of contact and consequent arching, not only limit the top velocity of high-speed trains but also imply the deterioration of the functional conditions of these mechanical equipments. To address such important aspects for the design and analysis of the pantograph-catenary system, it is necessary to develop reliable, efficient and accurate computational procedures that allow capturing all the relevant features of their dynamic behaviour. This work presents a computational tool and a modelling methodology able to handle the dynamics of pantograph-catenary interaction using a fully three-dimensional methodology. In order to exploit the advantages of using a multibody formulation to model the pantograph, a high-speed co-simulation procedure is setup in order to allow the communication between the multibody model and the finite element catenary model. A contact model, based on a penalty formulation, is selected to represent the interaction between the two modelling procedures. The methods and approaches developed here are used in realistic operation conditions for high speed trains. A series of studies of the dynamic behaviour of the pantograph-catenary system is presented, including experimental catenary models with single and multiple pantograph operation scenarios and overlap catenary sections in order to access the conditions that limit the increase of the trainset speed.

Keywords: Railway dynamics; Pantograph-Catenary interaction; Finite elements; Multibody systems; Contact mechanics; Co-simulation.
1 Introduction

The high speed railway systems are becoming key-players in worldwide transport policies. This results from the rising oil prices and from the urgency for reduction of CO2 emissions, among others. To improve the competitiveness and attractiveness of railway networks, the trains have to travel faster, with improved safety and comfort conditions and with lower life cycle costs. Furthermore, the railway operators are demanding reductions in the overall operational costs. They put particular emphasis on the railway vehicles maintenance costs and on the aggressiveness of rolling stock on the infrastructures. The quest for interoperability has in the compatibility of different pantographs with existing and projected catenary systems puts an extra level of demand on the ability to control their interface.

A limitation on the velocity of high-speed trains concerns the ability to supply the proper amount of energy required to run the engines, through the catenary-pantograph interface [1]. Due to the loss of contact not only the energy supply is interrupted but also arcing between the collector bow of the pantograph and the contact wire of the catenary occurs, as depicted in Figure 1.1, leading to the deterioration of the functional conditions of the two systems.

![Figure 1.1: Detail of the pantograph catenary contact, during the operation of a high-speed train, with the occurrence of dropper slacking and arcing.](image)

The complete study of design and operational alternatives for the mechanics of the overhead electrical system require that the dynamics of the pantograph-catenary are properly modelled and that software, used for analysis, design or maintenance support, is not only accurate and efficient but also allows for the modelling of all relevant details to the train overhead energy collector system. The European Strategic Rail Research Agenda [2] and the European Commission White Paper for Transports [3] have identified key scientific and technological priorities for rail transport over the next 20 years. One of the points emphasized is the need to reduce the cost of approval for new vehicles and infrastructure products with the introduction of virtual certification.
The work presented here follows this trend and proposes a modelling approach and a computational methodology gathered in a software tool that enables the dynamic analysis of pantograph-catenary interaction. The finite element method is used for the dynamic analysis of the catenary and a multibody dynamics approach is used for the dynamic analysis of the pantographs, regardless of being lumped or multibody models. A co-simulation environment is setup to run interference between the independent catenary and pantograph dynamic analyses. The methods proposed in this work are demonstrated in the framework of the application of the regulation EN50367 [4] to three case studies.

2 Catenary Modelling and Dynamic Analysis

High-speed railway catenaries are periodic structures that ensure the availability of electrical energy for the train vehicles running under them. A typical construction, such as the one presented in Figure 2.1, includes the masts (support, stay and console), serving as support for the registration arms and messenger wire, the steady arms, which not only support the contact wire but also ensure the correct stagger, the messenger wire, the droppers, the contact wire and, eventually, the stitch wire. Furthermore the functionality of the catenaries impose that spans have limited length, to allow for curve inspection and that the contact and messenger wires are not longer than 1.5 Km, depending each particular network.

![Figure 2.1: General structural and functional elements in a high speed catenary.](image)

Depending on the catenary system installed in a particular high-speed railway all the elements or only some of them may be implemented. However, in all cases both messenger and contact wires are tensioned with high axial forces not only to ensure the correct geometry, i. e., to limit the sag, guarantee the appropriate smoothness of the pantograph contact and ensure the stagger of the contact and messenger wires, but also to allow for the correct wave travelling speed to develop.
One of the critical parameters that limits the operational velocity of the trains is the wave propagation velocity on the contact wire, \( C \), which is given by [5]

\[
C = \sqrt{\frac{\pi^2 EI}{\rho L^2} + \frac{F}{\rho}}
\]  

(2.1)

where \( F \) is the tension of the contact wire, \( \rho \) is the contact wire mass per length unit, \( EI \) is the beam bending stiffness and \( L \) is the beam length. When the train speeds approach the wave propagation velocity of the contact wire, called critical velocity, the contact between the pantograph and the catenary is harder to maintain due to increase in the amplitude of the catenary oscillations and bending effects. In order to avoid this deterioration of the contact quality the train speed should not exceed 70-80% of the contact wire wave propagation speed [1]. For safety the maximum train operating speed, \( V \), is set to be \( V = 0.7C \).

The motion of the catenary is characterized by small rotations and small deformations, in which the only nonlinear effect is the slacking of the droppers. The axial tension on the contact, stitch and messenger wire is constant and must be considered in the dynamic analysis. Therefore, the catenary system is modelled with a linear dynamic finite element methodology in which the dropper slacking compensating forces, pantograph contact and gravitational forces are included in the force vector.

In this work, for the construction of finite element models of catenary systems, all catenary elements are modelled with a 3D beam element based on Euler Bernoulli beam theory [6]. This 3D beam element, which formulation is developed in [7], is assumed to be a straight beam of uniform cross section capable of resisting to axial forces, bending moments about the two principal axes in the plane of its cross section and twisting moments about its centroid axis. Also of importance about this 3D beam element is that it accounts for the stress stiffening on bending which is critical when modelling the contact and messenger wires that are subject to high tensioning. The one exception for the use of these beam elements are for modelling the claws and clamps that hold the structure together on the dropper/contact-wire/messenger-wire and steady-arm/contact-wire junctions; these are modelled as lumped masses.

To capture the dynamic behaviour of the catenary, an integration algorithm was implemented based on the implicit Newmark’s trapezoidal rule but taking into account specific modelling needs of the dynamics of the catenary model as for the dropper slacking and contact detection.

3 Pantograph Modelling and Dynamic Analysis

The railway roof pantographs are the systems responsible for collecting the energy from the overhead line. In order to guarantee a smooth operation, without losing contact with the contact wire or requiring an excessive contact force that, which lead not only to high wear but also large
uplifts of the steady arms, the pantographs must be dynamically responsive to the different range of frequencies with which they are excited.

The roof pantographs used in high-speed railway applications are of the type depicted in Figure 3.1(a). Mechanically they are characterized as mechanisms with three loops ensuring that the trajectory of head, while lifting the pantograph, is in a straight line, perpendicular to the plane of the base, while the pantograph head is maintained levelled.

The major differences between current pantographs reside not only on the raising mechanism constituted by the actuator and the lower stage but also in the pantograph head and its suspension. The numerical methods used to perform the dynamic analysis of the pantograph must be able to represent the important details of the system, including mechanisms and compliances and to evaluate their correct dynamics.

Two different types of models are generally used to represent pantographs: lumped mass and multibody. Each of them has advantages and shortcomings in their use that are discussed hereafter.

A typical multibody model is defined as a collection of rigid or flexible bodies that have their relative motion constrained by kinematic joints and is acted upon by external forces. The forces applied over the system components may be the result of springs, dampers, actuators or external applied forces describing gravitational, contact/impact or other forces. One of the criticisms to this modelling procedure is that the multibody model of the pantograph is made of rigid bodies connected by perfect kinematic joints.

Alternatively to a multi-body pantograph model another modelling method is commonly used consisting on a lumped mass approach. The lumped mass pantograph model, depicted on Figure 3.1(b), is composed of a simple series of lumped masses linked consequently to a ground by spring/damper elements.

![Figure 3.1](image.png)

(a) Representation of a pantograph; (b) Representation of the lumped mass pantograph model; (c) generic parameter values of the lumped mass pantograph

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While the multi-body pantograph models can be built with design data alone, for example with data obtained from technical drawings complemented with measured physical characteristics from selected components, the lumped mass pantograph model parameters, as the ones presented on Figure 3.1(c), must be identified experimentally. It is important to note that in spite of the simplicity of their construction, their dynamic response is accurate as the lumped mass models are commonly used by operators, manufacturers and homologation bodies instead of more complex models. The only part of the lumped mass model that as a physical interpretation is the upper stage, which limits the use of this type of models for any application that requires modifications on the pantographs structure or mechanics.

When using lumped mass pantograph models it is possible to use the same finite element code to solve the equations of motion of both pantograph and catenary. For this purpose, the pantograph is considered a linear system and its equations of motion must be assembled in the same way as the finite element catenary equations. The contact forces developed between the pantograph collector strip and the catenary contact wire are evaluated with the same contact model used one the multibody pantograph, and applied both on the appropriate beam element of the contact wire and the top mass of the pantograph.

It must be noted that this lumped mass pantograph model can also be easily integrated on a multibody application. The structures of the lumped mass pantograph model, in the multibody framework, include 4 rigid bodies connected by 3 translational joints, in the local z direction. In the same direction, joining each body to another, there is as spring-damper element with the characteristics depicted in Figure 3.1. A static force is applied to the mass \( m_1 \) in order to ensure a proper average contact force during the dynamic analysis.

4 Pantograph-Catenary Interaction

The contact involved in the pantograph-catenary interaction involves the pantograph collector strip and the catenary contact wire. The efficiency of the electrical current transmission and the wear of the collector strip and of the contact wire are deeply influenced by the quality of the contact. This implies that the correct modelling of the contact mechanics involved between these two systems is crucial for its accurate and efficient evaluation.

The contact between the collector strip of the pantograph and the contact wire of the catenary, from the contact mechanics point of view, consists in the contact of a cylinder made of copper with a flat surface made of carbon having their axis perpendicular as shown in Figure 4.1. In this work the contact problem is treated by a penalty formulation, where the contact force defined in function of the relative penetration between the two cylinders [8, 9].
In order to model the contact force using a penalty formulation it is necessary to geometrically access if there is contact and identify the contact location either on the pantograph collector strip or on the catenary contact wire. Also it is necessary to calculate the relative penetration of the contact accounting with the flexibility of the contact wire finite element.

The continuous contact force model used here is based on a contact force model with hysteresis damping for impact in multibody systems. In this work, the Hertzian type contact force including internal damping can be written as [10]

\[ F = Ke^{\delta} \left[ 1 + \frac{3(1-e^2)}{4} \frac{\delta}{\delta^*} \right] \]  

(2.2)

where \( K \) is the generalized stiffness contact, \( e \) is the restitution coefficient, \( \delta \) is the relative penetration velocity and \( \delta^* \) is the relative impact velocity. The proportionality factor \( K \) is obtained from the Hertz contact theory as the external contact between two cylinders with perpendicular axis. Note that the contact force model depicted by Equation (2.2) is one of the different models that can be applied. Other continuous contact force models are presented in references [11-13].

The interaction between the multibody pantograph and the finite elements catenary systems represents a coupled problem where the pantograph is a nonlinear dynamic system handled with variable time step and multi-order integrator, while the catenary is modelled as a dynamic linear system integrated with a Newmark family numerical integrator using a fixed time step. Generally the dynamic analysis of pantograph-catenary systems is done with both models using the same formulation, as in the case of the FEM lumped mass pantograph model.

However, if it is expected of the pantograph to exhibit large displacements and rotations during its operation, it is not advisable to model this system with finite elements method. Using the multibody methodology the analysis of pantograph-catenary interaction is done by two stand-alone and independent codes, the multibody pantograph and the finite elements catenary. A procedure to run simultaneously a multibody code and a finite elements code in a high-speed...
co-simulation environment, enabling real-time simulation of the pantograph–catenary interaction is developed on this work.

5 Applications to Overhead Current Collecting Systems

The computational analysis methodologies developed in this work are implemented in a software tool that handles the catenary dynamics and its interaction with the pantograph. With this tool, many scenarios can be built in order produce a wide range of simulations to reach any particular study of interest. Three case studies, each with its specific interest, were selected to be analysed and presented on this work. One case addresses a comparison between three pantograph-catenary pairs that are currently operating in Europe. Another case presents the analysis of multiple pantograph operation in high-speed trains involving a realistic catenary and a high speed pantograph model. A final case involves an analysis on a catenary with an overlap section in order to emphasize the transition between different sections of a catenary. The case studies evaluated are analysed in the framework of the application of the European regulation EN50367 and EN50317 [4, 14]

It is shown, on Figure 5.1, that catenary systems are very complex structures and can present a very different dynamic response among them. This is important when evaluating the contact quality that each catenary provides. However to achieve a better contact quality it is important not to consider the catenary and the pantograph systems independently as a factor of compatibility between both systems plays a fundamental role.

Figure 5.1: Contact force history along the catenary for three different pantograph-catenary pairs in current operation and comparison of their statistical analysis.
The application of the procedures to multiple pantograph operations, in high-speed railway vehicles, allowed the identification of the important quantities of the dynamic response that are required for the pantograph homologation and for operational decisions. The catenary damping plays a fundamental role in the pantograph-catenary contact quality. Catenary low damping leads to higher maximum contact forces, lower minimum contact forces, eventually to contact losses, and to higher standard deviations of the contact forces.

All these characteristics of the contact force lead to the rejection of the operation of multiple pantograph units at the required speed of 300 km/h in lightly damped catenaries. It is also concluded, from the results of the analysis, that for operations in average damped catenaries all standard separations between the pantographs lead to acceptable contact forces. As a general tendency, it was observed that for smaller pantograph separations the trailing pantograph affects the quality of the leading pantograph contact due to the wave travelling speed of the contact wire. For larger pantograph separations it is the leading pantograph that affects adversely the contact quality of the trailing pantograph, as shown on Figure 5.2. In any case, all results show that the critical separation between leading and trailing pantographs is 200 m, i.e., it is at this separation that the leading pantograph has a greater influence in the contact quality of the trailing pantograph.

Figure 5.2: Statistical quantities associated to the contact force between single, leading and trailing pantographs on a normal catenary section for different pantograph separations

It is also shown that the catenary damping plays a fundamental role in the pantograph-catenary contact quality, so it’s correct modelling is critical. However, it is recognized that the estimation of the structural damping of not only the catenary but other structures is still a technological challenge.

The numeric software tool developed here is also able to consider catenary overlap sections which represent a critical section on the catenary systems. These irregularities in the system can lead to increased contact force variation and thereby contact loss possibility. It was possible to identify that the uplift on the contact wire imposed by the pantograph-catenary contact has a great influence on the quality of the contact. The contact degradation is
particularly noticeable for the leading pantograph in multi pantograph operations when close separations between pantographs are used. Also, within the same reasoning, it was observed that the first pantograph passage eases the trailing pantograph transition.

6 Conclusions

The development of catenary and pantograph systems that allow their operation with higher speeds and better overall contact require that the computer tools used in their analysis include all modeling features relevant to their analysis. A computational approach based on the co-simulation of linear finite element and general multibody codes is presented and demonstrated in the framework of the pantograph-catenary interaction. It is shown that the use of linear finite elements are enough to allow for the correct representation of the catenary provided that the wire tension forces are accounted for in the stiffness formulation and that the droppers slackening is properly represented via the force vector. Minimal requirements for the catenary finite element modelling include the use of Euler-Bernoulli beam elements with axial tensioning and geometric stress stiffening for the catenary messenger and contact wire with a discretization enough to capture the deformation wave traveling of the contact wire. The dynamic equilibrium of the catenary system after each time step is attained with an iterative scheme in which displacements, velocities and forces are corrected.

It was also shown that the use of multibody dynamics methods allow capturing all of the important dynamic features of the pantographs. When multibody pantograph models are used, the co-simulation between the finite element and multibody codes must be ensured. The contact model between the pantograph collector strip and the catenary contact wire is used to achieve the co-simulation. Although other procedures exist, the use of a contact penalty formulation demonstrates to be enough to obtain all main contact features. The correct use of the co-simulation procedure, in which the minimal time step with which the problem can be solved is controlled by the finite element part, it is the challenging part of putting the dynamic simulation of these systems. The results of several case studies, presented in this work, demonstrate how all quantities used to characterize the dynamic response of the system are readily available from the pantograph and catenary simulation tools.
References

[14] EN50317 standard, "Railway applications - Current collection systems - Requirements for and validation of measurements of the dynamic interaction between pantograph and overhead contact line", CENELEC European Committee for Electrotechnical Standardization, Brussels, Belgium, 2012