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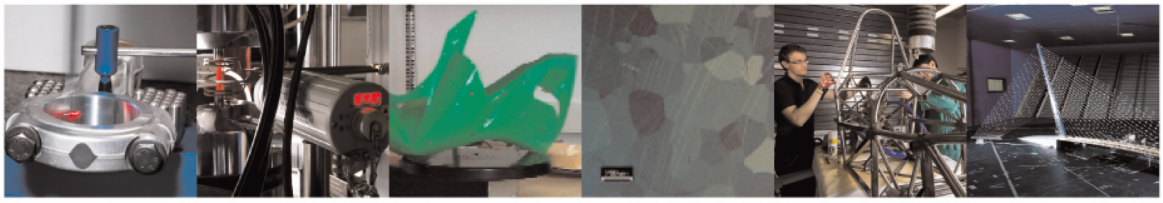

Recent developments on pantograph-overhead line Interaction

Stefano Bruni, Giuseppe Bucca, Alan Facchinetti, Santiago Gregori & Joao Pombo

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Recent Developments on Pantograph-Overhead Line Interaction

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Abstract

Railway transport plays a critical role in the socio-economic development of modern societies, breaking down barriers of distance and travel time, with recognized high levels of safety and comfort, and low carbon emissions. One crucial element for the reliable operation of electric powered trains concerns the energy collection system and the ability to supply a proper and uninterrupted source of electricity to the train, maintaining the required operational speeds with no losses of service. This paper presents a state-of-the-art on pantograph-overhead line interaction, including modelling methodologies, hybrid simulations, testing, wear and degradation mechanisms, aerodynamics and emerging trends in this area of knowledge.

Keywords: Pantograph-overhead line interaction, hybrid simulation, wear in pantograph-catenary systems, testing, pantograph aerodynamics.

1. Introduction

One crucial element for the reliable operation of electric trains concerns the energy collection system and its ability to supply a proper and uninterrupted amount of electric energy to power the traction vehicles and maintain the required service speed. The transfer of electric energy from wayside to the train is, in most cases, realised through the pantograph-OCL (Overhead Contact Line) interface, although in some cases this is obtained using a “third rail”. The OCL, also known as the catenary, is a structure composed of a set of suspended wires and supporting elements that run along the track and carry electric current to the train as required, see [1] for a description of different OCL systems. This current is collected by the pantograph, which is normally mounted on the roof of the train, via sliding contact between the OCL contact wire and the collector strips on the pantograph head. It is of the utmost importance to assure that this contact remains uninterrupted and is as stable as possible. Failure to do so breaks the power supply to the trains, compromising their operational performance. Improper contact conditions may also result in accelerated wear of the sliding surfaces and in the failure of components in the pantograph and in the OCL, as described below with more detail. Therefore, the interaction between the pantograph and the OCL needs to be carefully addressed to avoid service disruptions and keep maintenance costs within acceptable limits.
From a mechanical point of view, pantograph-OCL interaction is a coupled vibration of the catenary and pantograph caused by the spatial variation of the vertical flexibility in the OCL. When subjected to the force applied by the pantograph head, the contact wire undergoes a spatially variable uplift, causing a vertical movement of the pantograph head which leads to inertial effects in the pantograph head and deformation of the pantograph suspension, ultimately causing a dynamic fluctuation of the contact force exchanged between the contact wire and the pantograph head. Moreover, lateral

excitation of the pantograph/OCL system is caused by the lateral relative motion between the pantograph head and the contact wire caused by the stagger, i.e., the zig-zag placement of the contact wire, aiming to distribute wear effects over the width of the collector strips. Under specific service conditions, particularly at high speed and/or in presence of multiple pantographs, these effects become so serious that they hinder current collection. Furthermore, when the contact force becomes too low, arcing takes place between the contacting elements, which may cause severe local heating and intense erosion of the surfaces, a phenomenon known as "arc ablation", causing accelerated wear of both the contact wire and the collector strips. Current collection quality and wear issues are particularly severe for the so-called "Rigid Overhead Conductor Rails" (ROCRs) also known as "rigid catenaries" [1], [2] now being largely used in tunnels taking advantage from their reduced encumbrance. ROCRs, as their name suggests, are much stiffer than traditional OCL systems, and this causes higher sensitivity to geometric irregularities, i.e. deviations from the ideal geometry of the rigid conductor rail replacing the flexible contact wire.

Another major issue for conventional OCLs is represented by the excessive uplift of the contact wire at the supports, which may cause the interference of the pantograph head with the steady arm used to produce the stagger [3], [4]. This interference often leads to the failure of either the steady arm or the contact wire, resulting in the interruption of service on the track affected until the failure is repaired, with severe consequences in terms of train delays, service cancellations, economic penalties, etc.

Considering the above-described circumstances, it is apparent that pantograph-OCL interaction is a key aspect in the design and operation of modern railway systems, often representing a major limiting factor affecting their maximum service speed, as well as their reliability, availability and total life-cycle costs. In addition, new challenges are being posed to pantographs and overhead lines, e.g., associated to climate changes and new lines being built in desertic or high-altitude regions. Such situations are characterised by extreme weather conditions in terms of winds, temperature, icing, presence of sand or snow. These extreme climatic conditions need to be considered in the design of new pantograph-OCL systems and motivate new research to include their effects in the numerical models supporting the system design process and the definition of asset management procedures. At the same time, global warming effects are exacerbating the service conditions even for standard railway lines, so that in recent years issues have been reported regarding abnormal wear of the pantograph-catenary interface [5], [6], [7], crosswinds [8], sandstorms and thunderstorms [9].

To address the many open issues and research questions, the research effort spent on pantograph-OCL interaction increased significantly over the last two decades: a search performed on the SCOPUS database (keyword "pantograph AND catenary AND railway" searched within Article title, Abstract, Keywords) provides only 65 papers published before year 2004, 184 papers published from 2005 to 2014 and 504 papers published over the last 10 years from 2015 to 2024. It is the aim of this paper to review the recent progress of research in this sector, complementing other relatively recent surveys [9], [10], [11] and following the now historical review presented at the 15th IAVSD Symposium [12].

The paper is organised as follows: in Section 2 numerical models of pantograph-OCL interaction are presented. Section 3 presents hybrid simulation as an alternative to the numerical models described in the previous section. Section 4 presents testing methods and measurement techniques in view of their use for research and for the qualification of the pantograph-catenary couple. Section 5 provides an overview of research related to wear and other damage and their relation to pantograph-catenary interaction. Section 6 outlines the research status for pantograph aerodynamics and for the consideration of wind effects on the OCL. Finally, Section 7 summarises some emerging research trends and provides some concluding remarks.

2. Numerical modelling of pantograph-overhead line interaction

With the recent developments of computational tools that can study with detail the pantograph-catenary interaction dynamics, as demonstrated by the recent benchmark in this area [13], [14], there is now a larger consensus within the scientific and technical community on the reliability and benefits of these tools. For example, the railway industry now is more receptive to develop technology and perform authorization/homologation procedures based on numerical simulations rather than on in-line measurements, which are very expensive and time consuming. Therefore, it is essential continuing to develop reliable tools and testing procedures for the research and implementation of more resilient and cost-effective overhead contact systems.

2.1. Pantograph models

2.1.1. Pantograph description

The pantograph is a mechanical system responsible for collecting the electrical current from the catenary contact wire. In general, the pantograph is raised by a pneumatic actuator or by a raising spring installed at its base frame. The pantograph head is designed to exhibit a smooth raising movement, moving vertically in such a way that its contact strips (also known as collector strips) are always levelled and aligned vertically with the centre of the bogie to minimize deviations with respect to the track centreline during curves. The resulting uplift force is calibrated to achieve a contact force that is sufficient to prevent contact losses, but not excessive to avoid higher levels of mechanical wear on the contacting elements (see Section 5).
Different manufacturers present distinctive pantograph types but, in general, they have a similar topology, as depicted in Figure 1. They include at least two sets of suspension, one at the lower stage, between the base frame and the lower frame, and one at the pantograph head, supporting the contact strips. A third suspension set may be present in the knuckle area, connecting the lower and upper frames. The suspensions at the lower stage and in the knuckle are essential to smooth the raising and folding movement of the pantograph and are responsible for its frequency response at lower frequencies. The head suspension smooths the collector strips movement caused by the pantograph-catenary interaction and is essential for the dynamic response at higher frequencies [10],[15], [16].

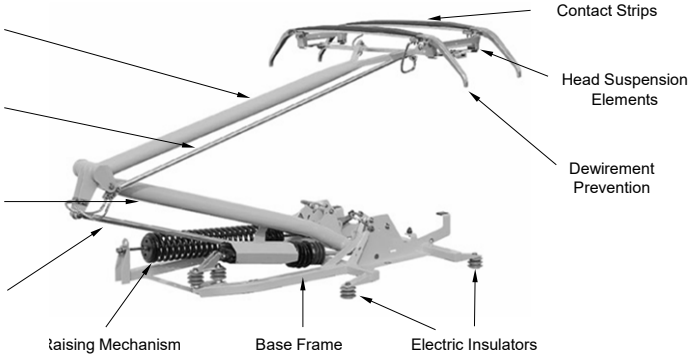


Figure 1: Main components of the pantograph

2.1.2. Pantograph Lumped Mass Model

The most common types of pantograph numerical models used to study the pantograph-catenary dynamics are the Lumped Mass (LM) and Multi-Body (MB) models. A LM model is a mathematical representation of the physical pantograph being composed by 2- or 3-stage mass-spring-damper elements, as represented in Figure 2. Usually, they are unidimensional linear models, with the masses only being able to move vertically, but can also include friction or force elements. The properties of the LM model are identified via full-scale testing of the physical pantograph, as specified in EN50318:2018 [17]. The pantograph is excited with different amplitudes and frequencies, in the

range 0.5 to 20 Hz [3], to obtain its Frequency Response Function (FRF). Then, an optimization algorithm is used to identify the mass, spring and damper characteristics of the LM model so that its frequency response is as similar as possible to the one of the real pantograph.

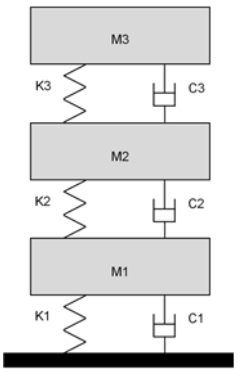


Figure 2: 3-stage pantograph lumped mass model

Typically, the LM models have 3-stage mass allowing the same number of resonance peaks, which are often observed in the vibration tests of the pantographs. The mass-spring-damper parameters of the LM model have little or no physical meaning, and changes on the physical pantograph cannot be reflected on direct changes to the LM model. Furthermore, the LM model is valid for a particular pantograph deployment height at which the vibration test is performed. Depending on the degree of nonlinearity of each pantograph, the LM model may be approximate for height configurations that depart from that of the physical test. However, no guarantee exists, a priory, that the accuracy is acceptable or that prescribed corrections of the model parameters can be assumed without further vibration testing.

2.1.3. Pantograph Multibody Model

An alternative to LM approach is to consider the Multi-Body (MB) formulation [18], [19], to study the pantograph dynamic behaviour by using rigid bodies connected by kinematic joints and force elements. The kinematic joints restrict the relative motion between the two connected bodies. Examples include the revolute joint, which only allows for rotation along one axis between the bodies, and the prismatic joint, which allows for translation along one axis. The force elements apply forces between two bodies, such as springs, dampers, actuators and bumpstops.

The MB methodology is fully 3D, as depicted in Figure *3*Figure *3*, and includes detailed information about the main parts of the pantograph and their linking and suspension components. It is initially modelled based on available technical drawings, preferably from 3D CAD models, enabling that the dimensions of the parts, masses and inertias are known with good precision. Force elements data are usually provided by the manufacturers. Although a MB pantograph model, solely based on CAD data, already has a good level of accuracy, it is required to be validated using dynamic response data, such as FRF, obtained in a test bench with the physical pantograph [17]. In this case, the tuning of the CAD data is made at the cost of the most uncertain data of the model, generally the nonlinear suspension or joint elements [20], [21], [22].



Figure 3: 3D pantograph multibody model

The MB models can emulate, not only the dynamic response of the pantograph collector strips while in contact with the OCL, but also the movement of the other mechanical components. In this formulation, the model parameters have a physical meaning, i.e., they represent a mechanical feature of the real pantograph, offering a dynamic response in the complete range of operation. Furthermore, changes in the physical pantograph can be directly reflected in the multibody model, which is very useful at the design stage for the refinement of the pantograph performance. Another advantage of the MB approach is that it enables considering the aerodynamic conditions and their effects on the pantograph elements [23], [24]. This includes the drag and lift force on the pantograph parts and how that affects the uplift, tilt and roll motions of the contact strips during the interaction with the catenary [25], [26], [27], [28].

An alternative MB modelling methodology is to consider flexible effects on the pantograph components [29], [30]. These flexibility effects only influence the pantograph dynamic response for frequencies above 30 Hz. In these cases, the pantograph numerical model is identified by using experimental modal analysis for extended frequency ranges up to 400 Hz [31], [32]. Such models allow studying pantograph-catenary interaction dynamics up to 100 Hz [32], [33], [34], aerodynamic effects on pantographs at frequencies up to 40 Hz [25] and high-frequency disturbances due to contact wire irregularities [35], [36].

Another aspect to consider when using pantograph MB models is that the numerical solver requirements are significantly different for the finite-element methodology, typically used to model the OCL, and for the large displacements and rotations associated to the multibody formulation. The usual way to solve this challenge is the adoption of co-simulation approaches between the finite-element and MB models [37], [38], [39], [40], [41].

2.2. Overhead line models

Railway OCL models have assisted catenary designers over the last 50 years, progressively gaining complexity and incorporating more features until becoming an indispensable tool supporting the design of new railway lines and the operation of existing ones.

In the early stages, analytical methods based on string [42] and beam [43] models, or using a time-varying stiffness [44], damping, and mass [45], [46], were proposed as simplified approaches to modelling the OCL. Despite these basic models are not able to consider all the complex behaviour of the system, they are still useful nowadays in analysing the interaction between pantographs in a multi-pantograph operation scenario [47], [48], wave propagation phenomena [49], [50], to perform hybrid simulations [51] and to assess control strategies for active pantographs [45].

Over the past two decades, the proposed models considered the messenger and contact wires as beams, accounting for wave propagation and reflection phenomena. Although some authors used the finite difference method [52] or an analytical modal approach [53], the Finite Element Methodology (FEM) has become the predominant technique for discretizing the resulting mathematical model [54], [55]. This fact was fully evidenced by the international benchmark exercise [13], [14], in which 9 of the 10 participant codes used the FEM to develop catenary models similar to the one depicted in Figure 4. Specifically, Euler-Bernoulli and Absolute Nodal Coordinate Formulation (ANCF) beam

elements are the main options used to model the contact and the messenger wires. Bar or spring elements with slackening are the most common options for modelling droppers, while steady arms are modelled with either linear mass-spring systems or bar elements. The different clamp types that connect the cables are considered as point masses. Despite some attempts to define more realistic cantilever models [56], their replacement by appropriate boundary conditions is the strategy generally followed in the current catenary models. Similarly, the tensioning device, located at both ends of a compensated catenary section, is usually replaced by displacement constraints.

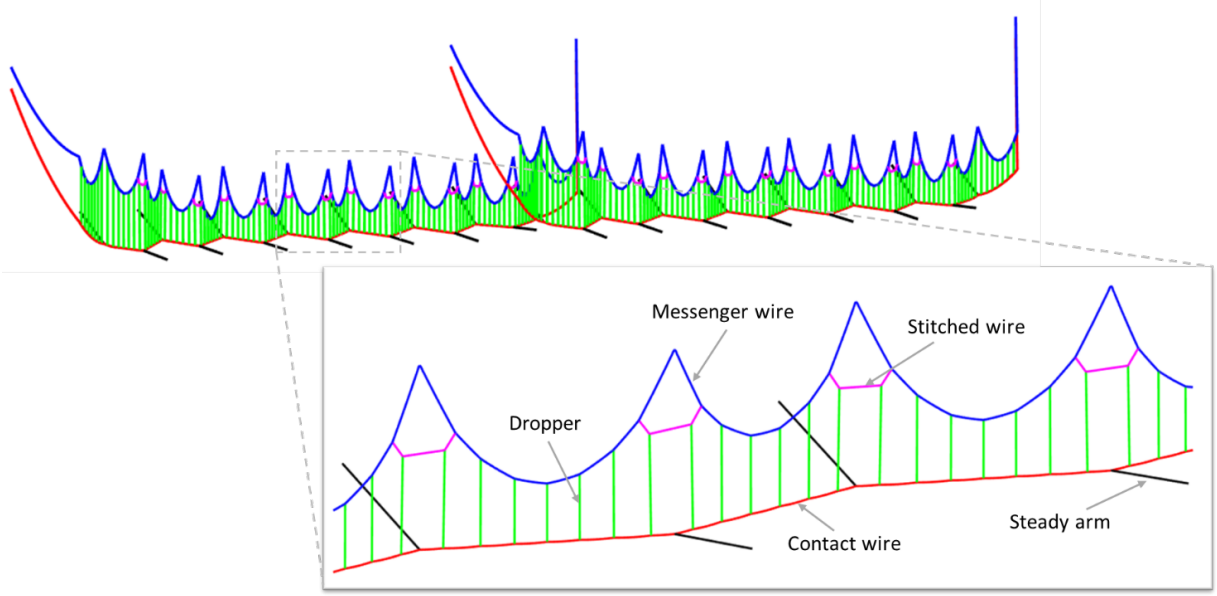


Figure 4: Finite element model of two catenary sections with an enlarged view of some spans indicating their main components

One important step before performing a dynamic simulation with a given catenary model is its initialization. It consists of computing the OCL initial configuration, in which the gravity effect is introduced, and some design constraints, such as the position of droppers and supports, the contact wire height, or the contact and messenger wire tension, must be fulfilled. A simple strategy proposed in [41] consists of computing the dropper forces and their initial length by splitting the contact and messenger wires and solving a static equilibrium problem on both elements individually. Based on linear beam formulations, iterative approaches are also found to obtain the initial configuration of the catenary model [39], [57]. However, these simple approaches do not consider the large displacements that the catenary cabling undergoes, and they are difficult to apply to actual track layouts with curves and gradients. To circumvent these limitations, nonlinear formulations are advised. From this perspective, the analytical expressions of nonlinear cable elements are used in [58] to compute the initial equilibrium state. Additionally, some approaches based on the ANCF are proposed, such as the improved formulation in [60] that avoids discontinuities in the axial force transmission, the dynamic equilibrium method in [59], or an adaptative variable-length cable element in [61].

In the pantograph-catenary dynamic interaction simulation, regardless of the formulation chosen in the initial configuration problem, the catenary model is linearized by assuming the small displacements hypothesis. However, the nonlinear behaviour of droppers [54] is kept to consider their slackening as the passage of the pantograph. It is a common practice to use a proportional Rayleigh model [14] although the damping coefficients are rarely known. Although some works dealt with their identification from full-scale measurements [62], [63] and their effects on the contact force [64], this is still an open research topic.

2.3. Pantograph-catenary contact model

The sliding contact between the collector strips and the contact wire is a critical aspect of pantograph-OCL dynamics, as it defines the interaction between the OCL and the pantograph which would be otherwise decoupled from each other. Modelling this contact presents some challenging issues. First, the contact is unilateral, i.e. only a compressive contact force can be transmitted between the contacting bodies. Secondly, the point of contact is moving along the contact wire. Thirdly, there are situations in which the same collector strip contacts multiple wires, e.g. in case of an OCL with double contact wire or in case of a transition between catenary sections. It should also be noted that the accurate prediction of the contact force exchanged between the collector strips and the contact wire (or wires) is a key objective of pantograph-catenary interaction. This is because the quality of current collection is defined based on the mean value and standard deviation of the contact forces, low-pass filtered in the 0-20 Hz frequency range, and also because dynamic fluctuations of the contact forces are strictly related to wear and damage effects occurring in the contacting bodies.

Pantograph-catenary contact can be modelled either as a sliding constraint or introducing a flexible contact element consisting of a linear spring and optionally of a viscous dashpot. From a theoretical point of view, the sliding constraint approach may look as a more rigorous option but entails significant issues. Firstly, the equations describing the coupling of the contact strip and contact wire motion are formulated in terms of algebraic equations which, together with the ordinary differential equations (ODEs) describing the dynamics of the OCL and of the pantograph, give rise to a system of differential-algebraic equations (DAEs), whereas the use of a flexible contact element gives rise to a state-dependent force which can be directly included in the ODEs realising the model of the pantograph and catenary. Secondly, the unilateral nature of the sliding contact requires that the coupling equations reflecting the presence of the sliding contact are activated and deactivated depending on the value of the contact force, which can only be compressive. Finally, in early applications of this method high-frequency numerical fluctuations of the contact force were experienced due to the interpolation of contact wire displacements between the nodes of the schematisation [12]. Recent implementations of the sliding constraint approach are found in the work by Pappalardo, Shabana and others [65], [66]. It is worth noting that, in these works, the sliding contact is applied in 3D and is assumed to constrain the motion of the contact strip to the contact wire both vertically and laterally.

The use of a flexible model of the sliding contact is more widely adopted in recent models of pantograph-catenary interaction, as attested e.g. by the comparison of the mathematical models involved in the 2015 benchmark [13]. In this approach, the position and velocity of the contact point on the contact wire and of the pantograph head are obtained from the coordinates used to describe the motion of the two subsystems. From these quantities, a virtual penetration δ and its time derivative $\dot{\delta}$ are obtained. Then, the contact force F_c is defined according to a unilateral spring-dashpot element:

$$\begin{cases} F_c = k_c\delta + c_c\dot{\delta} & \text{if } \delta > 0 \\ F_c = 0 & \text{otherwise} \end{cases} \tag{1}$$

with k_c and c_c being the stiffness and damping parameters of the contact element. In some cases, e.g. [40], [67], the velocity-dependent component of the contact force is defined according to the impact force model by Lankarani and Nikravesh [68]. The flexible contact model described by Eq. (1) can also be seen as an application of the penalty method in which the exact fulfilment of the sliding contact constraint is represented by the condition $\delta = 0$. This is enforced in an approximate way through the definition of a penalty function, the contact force, whose value is increasing for increasing violation of the constraint condition. Using a flexible model of the sliding contact results in a simple and efficient implementation, but the accuracy of the model strongly depends on the value of the stiffness and damping coefficients. A survey conducted on more than 30 papers published since year 2005 shows that in most cases the damping coefficient c_c is set to zero. This is probably due to the

fact that defining the velocity of the contact point on the contact wire involves the consideration of convective terms related to the sliding of the contact point along the wire. As far as the stiffness coefficient k_c is concerned, in most cases the value adopted is 50 kN/m, which is the value stated by the EN 50318 standard [17]. However, the results of a sensitivity analysis performed as part of the PantoTRAIN project showed a difference in the range of 8% for the contact force standard deviation between two simulation results referring to the same case (a high-speed pantograph running at 300 km/h in contact with a simple catenary designed for maximum service speed of 300 km/h) but using two different sets of values for the parameters of the contact model, namely $k_c = 200$ kNs/m, $c_c = 390$ Ns/m and $k_c = 50$ kNs/m, $c_c = 0$. In [54], a quantitative analysis of the sensitivity of results to the stiffness and damping parameters of the contact model is performed considering a simple test case. It is concluded that the flexible contact model provides sufficiently accurate results provided the frequency response function between wire and collector displacements, z_w and z_c respectively, is sufficiently close to the unit value for the simple 1-DOF model consisting of the contact strip (considered as a rigid mass) suspended by a spring with stiffness k_c and a viscous dashpot with damping constant c_c.

3. Hybrid simulation

Hybrid simulation (HS), also known as Hardware-in-the-loop (HiL) simulation, is a testing approach that integrates a physical component (hardware) under test with a computational environment (software). In the case of pantograph-catenary interaction, the pantograph is the element under test while the catenary is simulated in a computer. As schematically depicted in Figure 5, an actuator applies a given displacement to the collector strips and the force reacted by the pantograph is measured and sent to the computer as an input of the catenary simulation. The catenary vertical uplift produced by the measured force is computed according to the catenary model and sent as a reference position to the actuator, closing the loop. The dynamic simulation of the catenary must be performed in real time to reproduce the interaction between the physical and the virtual system. Due to the real-time requirement, the catenary models used in hybrid simulations often incorporate various simplifications that somewhat limit their accuracy and application scenarios.

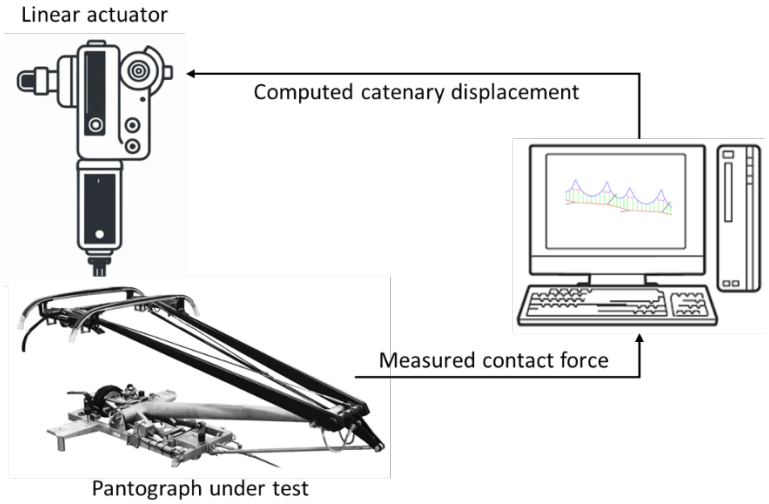


Figure 5: Schematic representation of a pantograph-catenary hybrid simulation.

The first reference to pantograph-catenary hybrid simulation dates back to 2002 from Southwest Jiaotong University [69]. Their test rig included a servo-hydraulic system to reproduce both the train movement on the basement of the pantograph and the contact strips movement caused by the contact with the catenary. The catenary model consisted of five equal spans modelled using a modal basis and droppers were treated as linear springs. This test rig was used in [70] to study the dynamic behaviour of four types of pantographs.

Another test rig able to perform pantograph-catenary hybrid simulations is available at Politecnico di Milano [71], [72], [73]. The vertical movement is accomplished by an electrohydraulic actuator and the test bench also includes lateral movement to reproduce the stagger of the catenary with an electric motor. The real-time catenary model, with a length of 3 or 5 spans, consists of two tensioned beams joined by non-linear droppers. The catenary dynamics is represented by modal superposition, and a shift-forward strategy allows to minimise the effect of boundary conditions.

At TU Wien, a more complex hybrid simulation approach was proposed [74]. The catenary model used is based on the use of moving coordinates and boundary layers to avoid wave reflections at the boundaries of the domain [75]. The central difference scheme was used to discretize the catenary equations of motion. The test rig includes an industrial robot arm with an electric linear drive. This approach includes an impedance control realized via Model Predictive Control (MPC) to guarantee stability in the tests.

The latest tests performed at RTRI in Tokyo in conjunction with the University of Bristol were presented in [76]. The proposed method is based on a dynamically substructured system framework to avoid instabilities caused by delays or modelling errors. The test rig includes a hydraulic actuator to impose vertical displacement on the pantograph. The catenary is simulated by discrete masses connected with spring and dashpot elements, from which the motion of the contact wire is computed using a set of modal coordinates.

A research group from Universitat Politècnica de València also published some works on this topic. Their test bench [77] includes an electric actuator to reproduce the catenary vertical movement and was recently updated with an additional actuator to consider the catenary stagger. Two catenary models were used for the tests. The first [51] consists of an infinite tensioned string supported by a viscoelastic layer, while the second is a periodic finite element model with non-linear droppers [78].

All the works described above considered in some ways a periodic arrangement of the catenary in their hybrid simulation approaches. Two different alternatives have been recently published to overcome this limitation. In the first [79], a general finite element model of an entire catenary section is solved in real-time following the solving strategy proposed in [80], and a Linear Quadratic Gaussian controller was used to ensure the stability of the HS. In the second [81], the interaction between the physical pantograph and the virtual catenary is accomplished iteratively so that the computations are not performed in real time, thus allowing the use of complex catenary models.

In summary, HS or HiL testing offers a promising method for reproducing the dynamic interaction between pantograph and catenary in a laboratory setting, as an alternative to expensive and complicated in-line testing. However, it is presently an emerging technique that requires further research to achieve a sufficient degree of robustness and reliability required for its broad application in the railway industry.

4. Testing of pantographs and OCL

Experimental tests are an important part of the design and qualification process of pantographs and OCLs. On the one hand, experimental tests represent the current means of assessment of the single components and of their interaction, according to relevant standards [3], [82]-[86], and the source of data for the validation of simulation tools [17]. On the other hand, experimental tests are fundamental to characterize some aspects of the components' dynamics, in terms of pantograph dynamic response, pantograph aerodynamics and damping of the OCL. Depending on their main scope, tests can be either performed in a laboratory or on track. In the following, the most common measurements and tests performed on the pantograph and on the OCL are described. Specific aspects related to pantograph aerodynamics are described in Section 6.

4.1. Laboratory testing of pantographs

Standard laboratory tests to assess pantograph dynamics can be conducted using multi-purpose test facilities that apply vertical excitation to the pantograph collectors. However, some laboratories have developed and currently use specialized test rigs specifically designed for dynamic testing of pantographs. In this respect, Figure 6 shows the HiL test-rigs in use at the laboratories of Politecnico di Milano, Dipartimento di Meccanica [73] and at the Institute of Railway Research, University of Huddersfield [87], which are also adopted to perform evaluation and characterisation of pantograph dynamics.

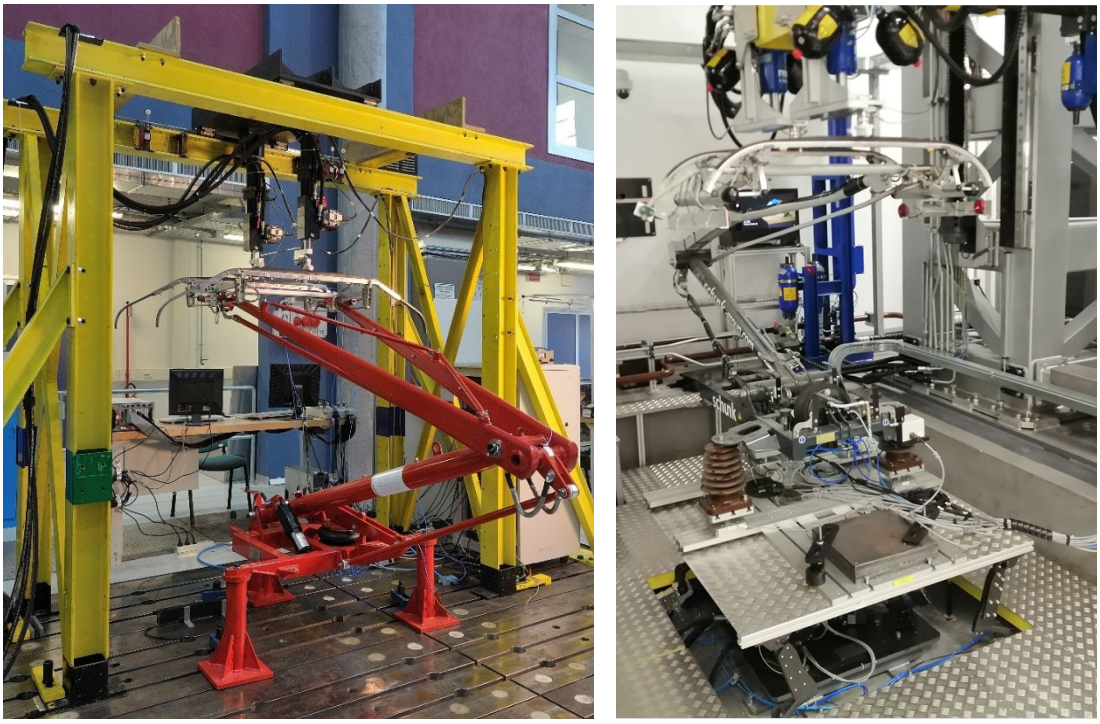


Figure 6: The pantograph HiL test-rig at Politecnico di Milano [73] (left) and University of Huddersfield [87] (right).

The pantograph test facility at the University of Huddersfield [87] is equipped with electronic systems to control the movement of the bench actuators in order to apply the loads on the pantograph collector strips. These vertical loads and stagger represent, in real time, the dynamic interaction that is developed between the pantograph and the catenary while in service. The pantographs are mounted on a 6 degree-of-freedom motion platform that can replicate any train movement or vibration.
Another example of a dedicated test-rig is that of DB Systemtechnik in Munich [88]. The main peculiarity of this test stand is the combined use of two actuation systems to move vertically the pantograph head, one to perform slow movements with large amplitude and the other to apply fast movement with small amplitude. In this way, it is possible to test the pantograph in its entire working range. The same layout is adopted for the test-rig available at the State Key Laboratory of Rail Transit Vehicle System in Chengdu [89] which also provides the possibility to apply a prescribed motion to the pantograph base.
The vertical excitation is typically applied to the pantograph collector(s) using hydraulic actuators. The test rig developed by the University of Birmingham, however, utilizes electric drives for actuation [90]. This test rig is designed to be installed in a maintenance depot to test pantographs on train roofs.
Test rigs are commonly employed to conduct type and routine tests in accordance with specific standards [85], [86], such as raising and lowering endurance tests or verification tests for the static

contact force variability in the pantograph's working range, to characterise the dynamic response of the pantograph and to calibrate measurement systems intended for use in line tests.
The characterisation of the pantograph dynamics is conducted both to ensure compliance with the design targets and to calibrate/validate models for numerical simulation, particularly when adopting lumped parameter models (see Section 2.1.2). To this aim, Frequency Response Functions (FRFs) between the vertical force on the collector(s) and the panhead motion (often also the upper and lower frame motion) are obtained applying imposed motion to the collector(s) and acquiring the response with suitable instrumentations, as depicted in Figure 7, most commonly accelerometers.

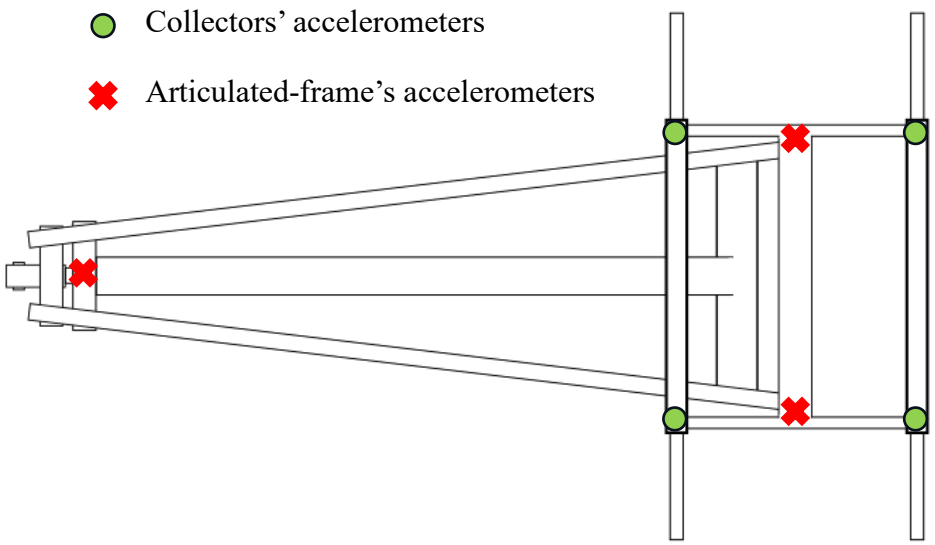


Figure 7: Common instrumentation scheme for pantograph dynamic characterisation

The excitation signals are usually swept sines or simple sines at different specific frequencies [17], [91]. The amplitude of the excitation should be selected to introduce appropriate energy in the system and to be representative of the actual pantograph operating conditions. In this respect, the applied excitation amplitudes can be inversely proportional to the excitation frequency, fixed to different values in different frequencies ranges, or set to obtain a target constant dynamic-force amplitude as suggested in [17].

4.2. Track testing of pantographs and OCLs

Track tests represent the final step for the assessment and qualification of a pantograph or of an OCL. Moreover, the obtained experimental data are crucial for tuning and validation of simulation models. With reference to the European Technical Specifications for Interoperability (TSI) [82], [83] and related EN standards [3], [84] (but the same approach is mostly adopted worldwide), the following parameters are considered to evaluate and assess current collection quality and interacting systems' performances:

- mean contact force as a function of train speed;
- contact wire uplift at the support;
- dynamic variability of the contact force, in terms of standard deviation of the contact force;
- percentage of arcing.

For current collection quality assessment, the analysis of the standard deviation of the contact force and of the percentage of arcing are considered as alternative methods, even though they are not proven to give the same results.

Most commonly, the contact force is measured by means of load cells placed between the collector and the related suspension, compensating the collector inertia by means of suitable accelerometers and the collector aerodynamic lift by means of an estimation obtained through prior dedicated tethered tests [84] (see section 6). The measuring system, composed of the load cells and of the accelerometers, is calibrated and checked in the laboratory [84]. It is worth remarking that the validity of this contact force measurement method is limited to the 0-20 Hz frequency range, since it relies on the assumption of collector(s) rigid motion for inertia compensation. Future developments aim to overcome the frequency limit [33]. To achieve this, it is essential to consider collector deformability [32].

The above-described setup typically relies on electrically powered sensors and signals, which present challenges related to electrical insulation. These issues are generally addressed by employing battery packages mounted on the vehicle's roof for power supply and converting electrical signals to optical ones [1]. In recent years, the implementation of optical load cells and accelerometers has been proposed and successfully implemented as an alternative [92], [93].

Other measuring systems are based on strain gauges directly installed on the collector [94] or at the interface between the collector strip and the collector frame [95], [96], [97], but these systems are not yet considered mature enough for evaluation and assessment purposes.

Considering arcing detection, the main advantage of the method is that it is not invasive, being based on the optical measurement of the duration of ultraviolet emission caused by electric arcing [84], [98], or in general on the combined use of cameras and specific signalling process techniques or algorithms to analyse images ([99], [100], [101]) Conversely, the simple knowledge of arcing occurrence is not sufficient to analyse the reasons that lead to the observed performances of the interacting systems. It is worth mentioning that there are few studies aimed at indirectly detecting arcing occurrence from electrical measurements already available on the vehicle, namely supply voltages and currents [102], [103].

The analysis of interaction performance is typically completed by measuring catenary motion. The standards require verifying the contact wire uplift at supports to ensure that the prescribed clearances between the pantograph and the infrastructure are maintained. In this respect, the most critical scenario usually involves multiple pantograph operation, possibly causing OCL resonance effects on account of the pantograph spacing and vehicle speed, that may lead to excessive contact wire uplift.

Besides the contact wire uplift required for assessment and qualification purposes, other measurement of OCL motion can be performed to better characterise and monitor the dynamic behaviour of the OCL. In [104] a dedicated wireless device is developed and proposed to measure wire accelerations at any location of interest, whereas vision-based measurements are proposed in [63].

It is worth remarking that one of the crucial aspects, also in view of the numerical simulation of pantograph-OCL interaction, is the definition of the damping properties of the messenger and contact wires. At present, this definition entirely relies on track tests or historical experimental data addressing the catenary response to an imposed excitation or following the pantograph passage [62].

5. Wear and damage

Wear and damage occurring both in the OCL and in the collector strips are a major issue affecting maintenance costs, reliability and availability of the railway system. In particular, wear phenomena at the sliding contact between the pantograph and the OCL have been the subject of intensive research. First studies of this topic date back to the first half of the last century [105]. In that reference, technical comments and observations based on the first years of operation of four electrified railway lines in the USA were presented, focusing on the influence of different parameters on the contact wire wear. The main parameters considered were: i) the design of overhead system and pantographs, ii) the lubrication of the metal (steel) collector strips, iii) the presence of steam locomotives under catenary, whose smoke containing particles produced by the combustion adheres to the grease film on the wire forming an abrasive layer, iv) icing of the contact wire, v) train speed and vi) the amount of current

collected. It is interesting to note that, except for point iii), the main factors affecting wear of the pantograph-OCL couple remain the same after nearly one century. However, the higher demands placed on electric traction in terms of higher speeds and increased current flow through the sliding contact exacerbate wear effects, so that recently cases of “abnormal” wear phenomena have been reported under particularly severe operating conditions in lines characterised by very high values of direct current collected [6], [7], [106], [107].

The typical appearance of the worn surfaces of the contact wire and of a carbon-based collector strip are shown in Figure 8. The contact wire shows a flat bottom, caused by material removal and the surface interacted by the contact with the pantograph shows clear signs of scratching. The worn collector strip shows a marked thickness reduction in the central part, with scratches and local voids which may be caused by the detachment of carbon flakes, like in the case shown in the figure, or by erosion craters resulting from arc discharge.



(a)



(b)



(c)

Figure 8: Worn surface aspect of a: (a) contact wire; (b) carbon-based collector strip; (c) detail of image (b)

Research on the wear of collector strips and contact wire involves extensive testing, mainly by means of laboratory tests performed on specimens of collector strips and contact wires. Field tests are less common due to the cost and time required. Laboratory test rigs have been designed and developed by several research groups [108]-[114] to perform tests and measurements under strictly controlled conditions. These test rigs are typically designed according to the block-in-ring configuration, as depicted in Figure 9. It consists of a disk to which the wire specimen is connected forming a ring on its perimeter. The collector strip specimen, which can be either the entire strip or a specimen block extracted from the real component, is pressed against the wire using an actuator and is subject to a radial reciprocating motion to reproduce the effect of the stagger in the real catenary. The sliding speed caused by the spinning of the contact wire rig can be as large as in the real system. For instance, a maximum speed of 500 km/h is stated for the rig described in [114].

An important feature of block-in-ring test rigs is that they are fitted with an electrical circuit allowing electric current flow through the sliding contact. Some test rigs can reproduce both Alternating Current (AC) and Direct Current (DC) conditions, while others only consider AC current. Finally, to correctly reproduce the thermal conditions of real service, some test rigs e.g. the one described in [110] incorporate a ventilation system convoying an airflow in the region of contact between the specimen wire and strip. The ventilation system is operated to produce a speed of the airflow matching the peripheral speed of the wire ring, thus reproducing the same relative speed between the air, the contact wire and the contact strip as in the case of a pantograph moving in still air. Moreover, to analyse the effect of environmental conditions, especially in terms of ambient temperature and humidity, on the wear, in some case the block-in-ring test rig is enclosed in an environmental room where temperature and humidity are controlled ([7]). Indeed, as reported in [7], [115], [116], especially the environmental humidity can have an important effect in the wear of contact strip and contact wire.

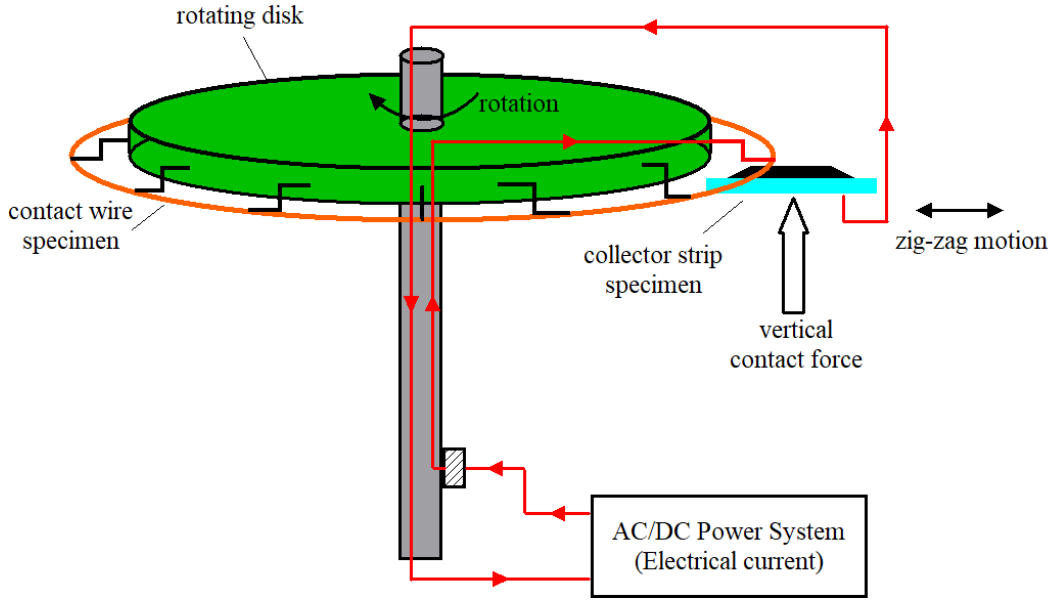


Figure 9: Schematics of a general block-in-ring configuration for a test rig

The results of extensive testing show that the total wear of the collector strip and contact wire is due to three main contributions [110], [117]-[121]:

i) mechanical wear due to abrasion, oxidation and surface fatigue;
ii) electrical wear due to heating caused by the Joule effect;
iii) electric arc erosion, due to intense heating produced by electrical arcs occurring in case of contact loss.

These three fundamental wear mechanisms show complex interactions between each other. For instance, the wear rate of carbon-based collector strips shows a V-shaped trend as a function of the

contact force [118], [121]-[126]. Indeed, low values of contact force produce an increase of electrical resistance at the contact and hence an increase of the electrical contribution, while too high values of contact force cause an increase of mechanical wear. The factor having the most important effect on wear is the intensity of electrical current flow. Electrical current flow promotes the formation of an oxide film on the contact wire reducing the coefficient of friction and hence mechanical wear, an effect known as "current lubrication". However, under high values of current flow, the effect of electrical wear and arcing becomes predominant, and the wear rate is increasing more than linearly with increasing current flow [127]-[130].

The wear behaviour of the collector strips and contact wire can be synthesised in the form of wear models, i.e. formulae defining the expected wear rate of the component as a function of different parameters, typically including contact force, sliding speed, intensity of electrical current flow and ambient factors such as temperature and humidity. Wear models can be divided in two different categories: models based on identifying the main wear mechanisms as a function of the operating conditions [110], [126], [131]-[133] and heuristic models based on the direct relationship between the wear rate and the main factors affecting the wear process [118]-[121],[134].

The use of a wear model in combination with pantograph-catenary dynamic interaction models allows to simulate long-term wear phenomena [110], [118], [135]-[140], supporting the design of new pantograph-catenary systems with the aim of reducing wear and, consequently, maintenance costs. The simulation process of long-term wear behaviour for the pantograph-catenary couple is illustrated in Figure 10. Starting from an initial profile of the contact wire and collector strip(s), the numerical simulation of pantograph-catenary interaction is performed using the methods presented in Section 2 of this paper and the time histories of the contact force and contact point position are obtained for all points of contact between the OCL and the pantograph (or pantographs). For each contact point, the electric resistance is estimated as a function of the contact force and then the electric current flow through the contact is determined. Next, the amount of worn material and wear depths on both the collector strips and contact wire are computed using suitable wear models. Wear depth scaling is applied to consider the effect of multiple vehicle runs, under the assumption that the wear rate is sufficiently small that significant alteration of the profiles is produced only after a sufficient number of runs is cumulated. Through this process, the geometry of the collector strips and contact wire is updated. Finally, the updated geometry is used to perform a new simulation of pantograph-catenary interaction, and the complete process is iterated to obtain the long-term prediction of wear [110].

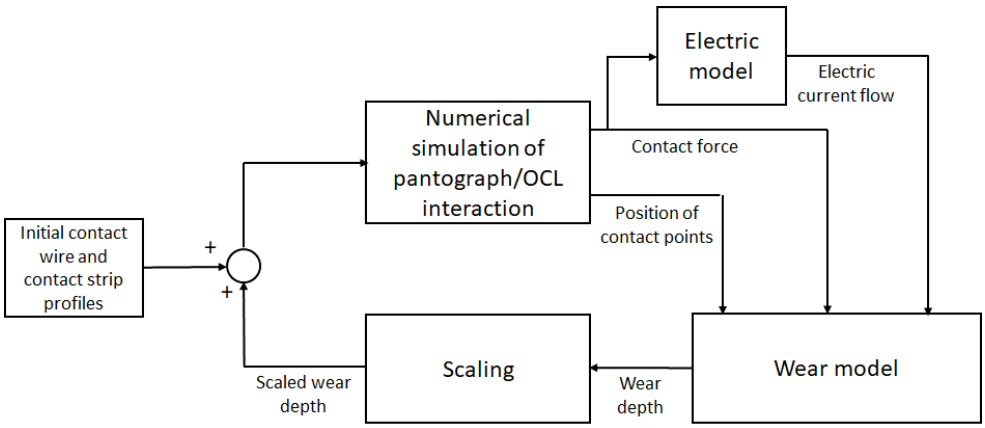


Figure 10: The simulation process of long-term wear for the pantograph-catenary couple

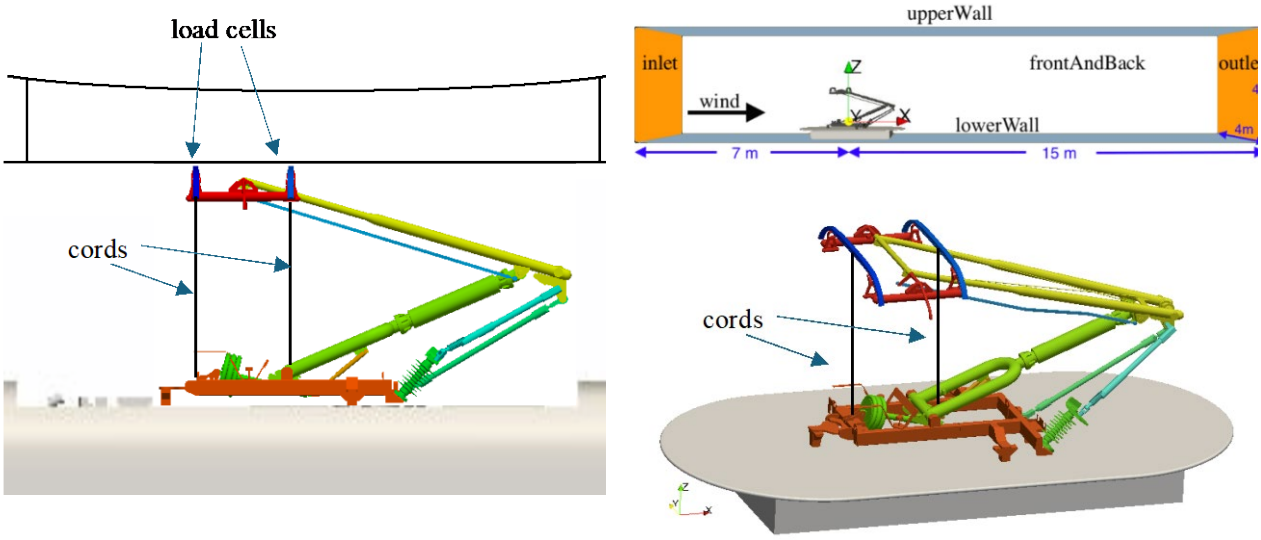
Despite wear is the type of damage most widely investigated for the pantograph-catenary interaction, research has been also performed regarding fatigue damage in the OCL, focussing in particular on bending fatigue effects in the contact wire [141]-[145], droppers [146], [147], and cantilever supports [148].

6. Aerodynamics

Aerodynamic actions, both on the pantograph and on the OCL, can significantly affect the pantograph-OCL interaction [8], [10], [23], [25], not only when dealing with high speed applications but even in conventional operation [149].
Focusing on pantograph aerodynamics, different contributions can be highlighted, affecting different frequency ranges:

- steady-state contributions due to the relative flow associated with the vehicle motion and to the stationary wind;
- low frequency contributions due to wind variability and to unsteady aerodynamic effects related to the turbulence of the incoming flow;
- high-frequency contributions introduced by vortex shedding from pantograph components.

The most relevant effect is caused by the steady-state drag and lift forces acting on the moving parts of the pantograph due to the relative flow associated with the vehicle motion in still air. These forces result in an uplift contribution, usually referred to as aerodynamic uplift, that alters the mean value of the contact force [23], [150]. The aerodynamic uplift depends upon the vehicle speed, the working height of the pantograph [8], [151], the pantograph orientation [26], [152], [153] (considering that most pantographs are asymmetric), and the position of the pantograph on the train roof, on account of the roof boundary layer that affects the flow velocity profile [153], [154].
To tune the aerodynamic uplift, spoilers are sometimes adopted [155], but their selection is complex considering that it is very difficult to optimise their tuning for both pantograph orientations. Moreover, the introduction of spoilers can worsen the dynamic behaviour on account of the turbulence of the incoming flow.
To date, the evaluation of aerodynamic uplift primarily depends on track tests, not only for certification purposes but also for design optimisation purposes, such as the addition of spoilers which is mostly performed based on a trial-and-error approach. In this context, “tethered tests” are commonly utilised, as outlined by [84]. In these tests, pantograph collectors are secured with cords to maintain their proximity to the contact wire without actual contact (Figure 11a). The forces measured in the cords represent the forces that the pantograph would exert on the contact wire, consisting of the static preload and the total aerodynamic uplift of the pantograph. Conducting tests at varying vehicle speeds allows to determine the global aerodynamic uplift as a function of speed. It is worth mentioning that the same kind of tests are used to define the collector aerodynamic lift, needed for contact force measurement, as the difference between the cord force and the force measured by the collector load cells [84] (see Section 4).
Wind tunnel tests represent a viable alternative to line tests, adopting a similar testing configuration shown in Figure 11b. This approach permits the assessment of aerodynamic performance for different design solutions under controlled flow conditions. The primary challenge of wind tunnel tests lies in accurately replicating the boundary layer of the train roof and, as far as possible, the turbulence conditions of the wind flow. The importance of reproducing the boundary layer to assess the uplift force in the wind tunnel is highlighted in [156], which also proposes an effective technique to develop a boundary layer with characteristics like those measured on the real train. However, this approach still depends on specific track tests for tuning and validation.

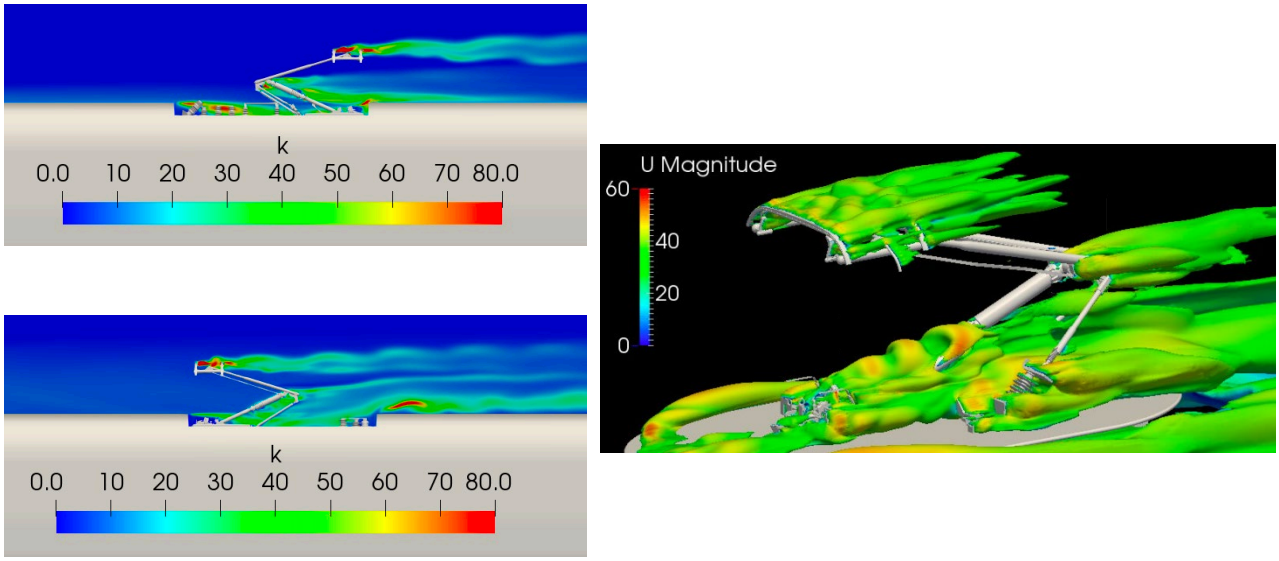


a) Set-up for track tethered tests.

b) Wind tunnel set-up.

Figure 11: Experimental evaluation of the pantograph aerodynamic uplift

Another possibility is to use wind tunnel data as a means to tune and validate Computational Fluid Dynamics (CFD) models [26], with no need to reproduce the actual roof boundary layer, and to extend CFD results to a real scenario with the pantograph placed on the train [26], [154].
Indeed, CFD is increasingly utilised to assess the impact of aerodynamic effects on the contact force, specifically in terms of aerodynamic uplift [26], [28], [153], [154], [157], [158]. In this respect, different approaches can be found in the literature, with either CFD models of the pantograph inside a domain that represents only the closer part of the carbody roof [158] or CFD models of the pantograph installed on the full train [26], [28], [153], [154], [157].
A key advantage of CFD calculations is that they evaluate both the overall aerodynamic force on the pantograph and the contributions from its parts, like the head and the arms [26]. This allows each part of the pantograph to be optimised to minimise effects such as the sensitivity of the mean contact force to train speed and the unbalance between the collectors [25], [152], that would result in power collection degradation and uneven wear of the contact strips.
It is worth mentioning that steady-state effects and the aerodynamic uplift may vary when the vehicle enters a tunnel, on account of the increased velocity of the relative flow [159], [160]. Moreover, also the presence of wind, changing the relative flow in terms of magnitude and direction, affects the steady-state aerodynamic uplift [23], [161], [162].
The presence of wind, crosswind in particular, may also affect the contact force contributions in the low frequency range, set by international standards for the evaluation of the quality of current collection (0-20 Hz in Europe) [25], [84], on account of the variability of wind around the steady condition. This disturbance is hardly quantifiable experimentally and is usually analysed numerically, joining CFD calculations and pantograph-OCL interaction simulations [161], [162], [163].
The same low frequency range is also interested by unsteady aerodynamic effects related to the turbulence of the incoming flow [164]: the presence of recesses [165], [166], car separation, electrical insulators [167] and other components installed on the train roof generate a turbulence wake (Figure 12a) that is likely to excite the pantograph in this frequency range. The turbulence can be even introduced by pantograph components, with the rear parts that are affected by the turbulent wake generated by the upwind ones. These aspects are also frequently addressed by means of CFD analyses.



a) Turbulent kinetic energy, steady-state RANS simulation for the full train.

b) Isosurface coloured by speed magnitude, unsteady URANS simulation for the pantograph.

Figure 12: Examples of turbulent flow on the pantograph

Finally, vortex shedding (Figure 12b) may introduce high-frequency excitation with an impact on aerodynamic noise [168], [169], [170] and on the collector flexural modes of vibrations, with possible negative consequences on the percentage of arcing and, more generally, on current collection quality. In this respect, most of the research work is focussed on aero-acoustic issues, addressed by means of CFD analyses [166], [171], [172].

7. Emerging trends and conclusions

This section presents some topics which have attracted increasing research interest in recent years and are likely to be further investigated in the future. Afterwards, some overall conclusions are presented.

7.1. Rigid overhead conductor rails

Unlike flexible overhead contact lines, ROCRs employ an aluminium profile to grip the contact wire along its entire length, eliminating the need for tensioning devices. Their main advantages are improved safety in operation, low clearance required for installation in tunnels, and reduced maintenance costs. However, the main limitations of this technology are the lower operation speed and the requirement of shorter span length compared to flexible catenaries.

Current research is paying more and more attention to this type of catenaries. Some numerical models can be found in the literature [173], [174] mainly based on the use of beam elements and equivalent stiffness to consider the supports. These models were used to evaluate the influence of several key parameters such as train speed, pantograph type, pantograph preload or span length [175], [176] and to perform parameter optimisation [177]. Additionally, the dynamic behaviour in specific scenarios like transitions between ROCRs and flexible catenaries [177], [178], expansion joints [179] or double pantograph operation [180], have also been analysed.

A parallel research stream focuses on improving the system performance from different viewpoints. In [181] a hybrid catenary with the rigid conductor held on a messenger wire is studied to enlarge the distance between the supports. New conductor rail sections are also proposed and analysed in [182], [183] aimed at increasing the bending stiffness of the ROCRs to decrease the static sag and, consequently, increase the operation speed without compromising safety. Another alternative design

proposed to mitigate catenary vibration resorts to the use of an experimentally validated tuned mass damper [184].

7.2. Active control

Active control of pantographs has long been regarded as a useful means to improve current collection quality [185], [186] and the number of related studies would deserve a dedicated review. An effort in this respect can be found in [187].

Despite this significant interest in active control, only a few documented cases have led to the development of active pantograph prototypes, which have been verified through laboratory experiments [72], [188], [189], [190] or track tests [191]. In fact, the only application that has been actually implemented is the simple regulation of the pantograph preload, as in use on the TGV fleet in France [192] or on the ETR500 and ETR1000 fleets in Italy [193].

Most of the studies are limited to the proposal of control strategies and to the theoretical or numerical verification of the achievable performances. This is because on one hand the actual implementation of an active pantograph poses several technical challenges, also considering the high voltage environment; on the other hand, the achievable improvements in terms of performances haven't yet demonstrated to justify the added complexity of a mechatronic pantograph, with unavoidable repercussions on construction and maintenance costs, reliability and availability.

The proposed solutions can be classified considering the actuation principle or the adopted control strategies. The actuation is usually introduced in parallel to the passive system and can be applied: on the articulated frame [12], [188], [190], [191], simplest configuration with no significant restriction on the actuator but very limited bandwidth (up to 1-2 Hz) [194]; in parallel to the collector head suspension [12], [188], [191], [194], increasing the bandwidth up to 20 Hz but imposing limitation on the actuator size and mass; directly on the collectors [45], [189], [195], [196], most effective configuration but hardest to implement. Clearly, the different configurations can be adopted at the same time [12], [188], [191].

Concerning the control strategy, two main approaches exist: the first consisting in the direct feedback of the contact force [188], [194], [195], [197], [198], requiring contact force measurement or estimation; the second in modifying and enhancing the dynamic behaviour of the pantograph [190], [199] - [201].

The proposed control techniques are various, ranging from simple PI/PID regulators [45], [188], [194], [197] to optimal control [199], [200], sliding mode control [195], [201], fuzzy logic [198] up to more recent machine learning techniques [202].

7.3. Condition monitoring of the pantograph-catenary system

Faults and malfunctions occurring in the pantograph and especially in the OCL may be the cause of critical disruption of railway service. Therefore, it is extremely important to adopt appropriate monitoring and maintenance practices, particularly ensuring that the contact wire maintains a proper geometry and detecting damage of components (e.g. droppers, regulation arms) before they cause serious faults. As a consequence, a vast research effort has been spent in recent years to establish advanced condition monitoring techniques for the pantograph-catenary system, also resorting to the use of Artificial Intelligence (AI) techniques. Collector strip monitoring can be performed using artificial vision systems [203] which can be installed in diagnostic portals placed at fixed locations in the line or hosted in maintenance workshops. The monitoring of the OCL, instead, can be performed using vehicle-mounted sensors such as accelerometers [204], [205] or fibre optics sensors [96] or using vision systems [206]. A thorough review of recent research in this field would require a review paper on its own, therefore here we confine ourselves to pointing the interested reader to the paper by Brahimi and others [207] providing a review of monitoring and prognostics methods for the OCL and to [208] for a focus on recent AI-based applications.

7.4. New materials

Studies on new materials for the pantograph/OCL couple are mainly concerned with the selection of suitable materials for the contact wire and the collector strips. As far as the contact wire is concerned, new copper alloys are progressively being introduced in place of pure copper, or electrolytic copper (Cu-ETP) to improve the wire's creep under tensile load. In particular, the CuMg alloy is used for applications in which the contact wire tensile load is 30 kN or higher, i.e. for high-speed and very high-speed applications. For DC lines, characterised by lower service speeds, the selection of the contact wire material is aimed at optimising conductivity and one frequently used material is the CuAg alloy, although in some cases also the CuSn alloy is used.
Regarding collector strips materials, the most widely used one is carbon, due to the good self-lubricating properties and acceptable conductivity. Pure carbon is mainly used for applications characterized by low values of collected current (normally below 500 A), while copper-impregnated carbon is used at higher values of collected current due to its superior electrical conductivity [209]. In recent years, some composite materials for the collector strips are being considered to investigate the possibility of improving wear performance of both the strip and the contact wire, increasing the service life of these two components. In [210], copper fibre reinforced carbon/carbon composite (C/C-CuF) and copper alloy impregnating carbon/carbon (C/C-Cu) for the collector strips were investigated to assess their wear performance with respect to pure carbon. Experimental tests showed that the two composite materials have better mechanical properties with respect to pure carbon but worse wear performance. In [211], another experience with a composite material, i.e. Cu/CF/phenolic resin, for collector strip is reported. This composite material presents a slightly lower resistivity compared to pure carbon while wear performances are similar. In general, until now carbon-based collector strips still represent the best trade-off between conductivity and resistance to wear, but research is ongoing to develop new materials.

7.5. OCL discrete features

Most of modern pantograph-OCL numerical tools can be used for performance verification against standards and regulations to simplify the authorization process. These studies are generally performed in straight tracks [13], [14] including overlap sections and insulators [212], [213]. However, the railway network also includes curved sections and other OCL features that need to be considered in some applications such as gradients, transitions to tunnels, neutral sections, section insulators and cross-overs [1], [214]. These discrete features introduce points of increased mass, inertia and stiffness on the overhead system, leading to hard-spots and the degradation of the contact quality. Furthermore, overbridges often require specific OCL geometric arrangements to ensure proper electrical gauging and meeting of safety requirements, such as reduced wire heights and/or contenaries. As real catenaries are much more complex than a simple straight and homogeneous model, the implications of discrete features and geometric singularities in dynamic simulation need to be addressed.
Recent works were published on the analysis of catenary gradients in straight track with MB and LM pantograph models [215], [216]. Other authors proposed a methodology to build catenaries with realistic geometries along the track, which includes curves, cant and vertical grades [54], [217]. Studies on general tracks and OCL geometries are also performed to study the pantograph-OCL interaction in such conditions [218], [219]. In all these developments, the finite element methodology is used as it is the most versatile approach for modelling an OCL, especially when specific configurations are investigated.

7.6. Overall trends conclusions

This review paper has hopefully highlighted the importance of pantograph-catenary interaction towards enabling the improvement of performance, availability and reliability of railway service and in view of the reduction of operational costs. In response to these needs, intense research effort is

being devoted to the topic. In terms of the present research status and outlook on future research needs, modelling and simulation of pantograph-OCL interaction is well established in the 0-20 Hz frequency range, but further research is needed to extend the numerical models to a wider frequency range, which is especially required to better understand wear and damage phenomena. The improvement of numerical models is strictly intertwined with the improvement of measuring methods aimed to extend the frequency range of the contact force measure using new sensor technologies. Furthermore, it is expected that, in the future, artificial vision systems will be more widely used, both as non-conventional measuring systems and for advanced monitoring purposes.

Another area requiring intense research is concerned with new materials. For the OCL the main need is to increase the contact wire tension, thus raising the wave propagation speed and enabling higher service speeds, while keeping under control creep effects. It should be noted that recent studies [220] explore the possibility to operate the OCL at super-critical speed as an alternative to increasing wire tension. On the pantograph side, research is oriented towards new materials for the collector strips, providing better performance compared to the existing ones in terms of the trade-off between conductivity and resistance to wear.

Finally, like in many other fields, increased use of AI and ML techniques is expected. Recently, the definition of surrogate models has been investigated as a means to increase substantially the computational efficiency of numerical models, with application to the optimisation of new OCL designs [221], [222]. Surrogate models could prospectively be used also to define digital twins (DTs) for pantograph-catenary systems. Furthermore, the use of DTs and AI-based methods for the purpose of monitoring the pantograph-OCL system is rapidly expanding [208], for diagnostics, avoiding faults in service, and prognostics, promoting the shift from corrective/preventive maintenance to predictive maintenance.

Overall, the topic of pantograph-catenary interaction appears as very lively at present, and likely to attract even more attention from vehicle dynamics experts than in the recent past.

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