Pantograph-catenary interaction: recent achievements and future research challenges

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ABSTRACT

This paper aims to provide an overview of the present status of research in pantograph-overhead line interaction and to outline future research challenges. A review of currently used modelling and simulation approaches is provided, also including hybrid simulation, and emerging trends are outlined. Then, line testing methods for the certification of pantographs and catenaries are described and the limitations of measuring methods now in use are highlighted. Issues related to the reliability and availability of the pantograph-overhead line system and to life cycle costs are then covered in the paper, particularly concerning wear and other damage phenomena and condition monitoring solutions enabling the efficient maintenance of the system. Pantograph aerodynamics and active control of pantographs are finally identified as two emerging trends of research. For both subjects, a review of problems currently at stake and of future research directions is provided.

KEYWORDS

Pantograph-catenary dynamic interaction, numerical simulation, HIL, laboratory and line tests, pantograph aerodynamics, active control

1 Introduction

In recent years, railways have known a substantial expansion across different continents. The impressive development of high-speed lines in China [1], the continuous expansion of the European network, the launching of direct train connection between China and Europe for freight and key projects launched in India, Turkey, former USSR Republics are just examples of the global tendency towards an increasing importance of railways in meeting transport needs for the global world. In this framework, improving pantograph-catenary interaction is a key issue towards enabling faster and more reliable operation of trains and, at the same time, reduce the maintenance costs for the rolling stock and the infrastructure.

For this reason, the effort spent in research on topics related to pantograph-catenary interaction has increased substantially over the last years: a search performed on the SCOPUS database shows that in years 2005-2006 only 19 papers were published having as their subject pantograph-catenary interaction. In years 2010-2011 this number had grown to 48 and in 2015-2016 there were 80 papers published on this subject.

The increased interest on pantograph-catenary interaction topics is also demonstrated by the funding of two research projects in the sixth and seventh framework programmes of the European Commission, namely EUROPAC [2] and PantoTRAIN [3], that led to interesting developments and helped to identify various challenges. Progresses in the establishment of mathematical / numerical models for the simulation of pantograph-catenary interaction were recently reviewed by a benchmark exercise that involved several research institutes across 9 countries in Europe and Asia [4]. The results of this benchmark allow to draw conclusions on the present status of simulation tools and also to provide a term of reference for new models being developed [5]. However, the benchmark strictly focussed on mathematical modelling and simulation, whilst there are other important areas in which research related to pantographs and catenaries is quickly developing.

It is therefore the aim of this paper to provide a comprehensive overview of recent research concerning all mechanical aspects related to the interaction between the pantograph and the overhead equipment (catenary). These include not only modelling and simulation, that are only briefly addressed having been the subjects of past [6] and recent [4,7] comprehensive works, but also testing and measurements (both in laboratories and in the line), wear and damage mechanisms, aerodynamics, health monitoring and active pantograph control. This review paper will not cover, however, aspects strictly related to the electric interaction between the pantograph and the catenary such as modelling of arching, electro-magnetic compatibility, electric disturbances generated by the train on the overhead power supply (so-called 'harmonics') and so on.

The paper is organised as follows: Section 2 provides an updated overview of the State-of-Art concerning the numerical simulation of pantograph-catenary interaction. Section 3 deals with the so-called 'hybrid' or 'Hardware-in-the-Loop' simulation of pantograph-catenary interaction, representing a recent development and offering prospective advantages over 'standard' numerical simulation. Section 4 describes methods for the testing and qualification of pantographs, with a focus on the measure of pantograph-catenary contact forces. Section 5 covers issues related with the condition monitoring and with wear and damage in the pantograph-catenary couple. Section 6 provides an updated State-of-Art review on the investigation of pantograph aerodynamics using both experimental and numerical methods. Section 7 summarises recent investigations concerning the possibility to improve current collection by means of active pantograph control. Finally, Section 8 draws some conclusions and identifies needs for further research.

2 Numerical simulation of pantograph-catenary interaction

Numerical simulation tools for the analysis of pantograph-catenary dynamic interaction are well established. Comparing the state of the art in mid 1990's [6] and in recent years [4,7] the evolution and spread of numerical models can be easily appreciated. Early approaches were based on simplified representation of the catenary as a spatially variable stiffness [8], whilst together with the increase of computational capabilities, a variety of simulation approaches has been developed and proposed. Most of the available tools are based on finite element modelling of the overhead catenary line (OCL), as shown in Figure 1, and lumped mass pantograph models (Figure 2a), adopting a penalty method to describe the flexible mono-lateral contact between the catenary and the pantograph [9-16]. In [17] a more general multibody model (Figure 2b) is introduced for the pantograph: this model is run in co-simulation with a finite element catenary model. The finite difference method is considered as an alternative to the finite element method for the spatial discretization of the catenary in [18] and is adopted by PrOSA [19]. The finite element or the finite difference models are the best choice for modelling the catenary because they allow to reproduce the effects of transversal wave propagation along the wires, which become very important for the multi-pantograph case. The slackening of the droppers results in nonlinear effects strongly affecting the dynamics of the pantograph-catenary system and, therefore, the inclusion of these effects also represents a key requirement in order to achieve realistic simulation results ([10,13]).

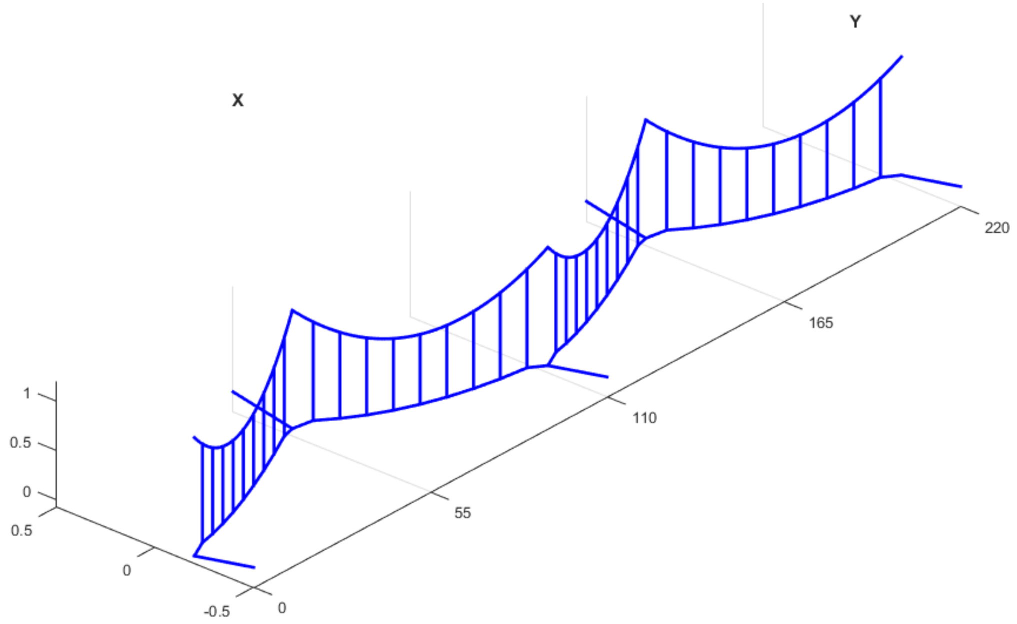
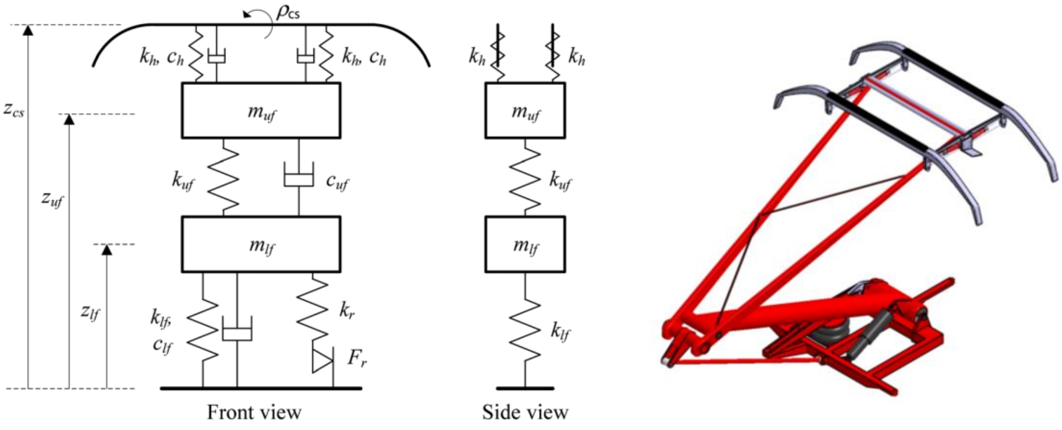


Figure 1. Example of FE representation of an OCL section.



a) b)

Figure 2. Pantograph models: a) lumped parameters b) multibody.

As demonstrated by the recent benchmark among simulation codes for pantograph-catenary dynamic interaction ([4,5]), affordable simulation tools are nowadays available and have reached a certain level of consensus within the scientific and technical international community. Most of these tools can be used for verification against normative requirements (e.g. the Technical Specifications for Interoperability – TSI in Europe) of the general design of a standard OCL, including overlap sections and insulators ([20,21]). Other OCL features sometimes need to be considered, such as neutral section with insulators, transitions to tunnels, rigid catenaries and the related transitions to and from standard OCLs: the possibility to model these special features of the line partially depends on the used approach. Under this respect, without discarding the importance of semi-analytical methods, the finite element method is by far the most versatile approach for modelling an OCL, especially when particular configurations are investigated.

Some numerical challenges and open points were pointed out in the "statement of methods" papers describing the numerical tools compared in the benchmark [4]. In particular:

- the initialisation of catenary models is a challenging task. In fact, the loaded geometry is reached after nonlinear deformations of the structure and, since most of the simulation tools adopt linear finite element models for the catenary, obtaining realistic initial geometry using a linear FEM code could be not trivial [22,23].

- a detailed analysis of actual catenary geometries and construction details, and of the kinematic compatibility between the pantograph bow and the contact wire may require the adoption of a full 3D representation of the overhead structure, taking properly into account also the presence of curves in the railway track [22,23].
- the adoption of multibody approaches can improve the representation of the pantograph, especially at design stage when it is not possible to experimentally identify/verify lumped-mass model. Solver requirements are significantly different for linear FE models and for large rotation multibody models and the best way to solve this inconsistency appear to be the adoption of co-simulation approaches [7,22,24,25].
- the structural damping associated to catenary elements appear to be a key parameter for accurate representation of the pantograph-catenary interaction, in particular when dealing with multiple pantograph operation. The improvement of simulation models is related, among others, to a better identification [26] and modelling of catenary damping, as pointed out in [7].

In the last years, researches have mainly focused on the development of efficient numerical method for real-time execution of catenary models (see next section) and to the generalisation of catenary models to large deformation analysis [27-31], adopting absolute nodal coordinates [27-29] or corotational formulations [30]. This aspect is of particular importance for studies concerning crosswind effects on OCL [30,31].

As far as the subject of simulation is concerned, due to the recent request to upgrade rigid catenary systems for speed up to 200 km/h and more, the need to create numerical model for this kind of catenary system is emerging for design aims [32-35]. In this case, it is mandatory to include all the features related to tolerances in installation, misalignment in correspondence of bolted joints, deviation from exact rectilinear shape of the standard bars, and other structural features such as transitions with the standard wires catenary, insulating sections and switches.

One additional challenge that can be tackled by means of numerical simulation is the optimisation of catenaries and pantographs for interoperability. It has been shown that the enhancement of catenary systems can greatly benefit from using optimal approaches to allow train operations at higher speeds in the existing networks [36] and that the national pantograph-catenary pairs are basically optimised with respect to the interaction quality [37]. The optimisation of pantograph for cross network operation is however a still open challenge.

3 Hybrid simulation of pantograph-catenary interaction

Hybrid simulation has recently emerged as an enhanced way of simulating the dynamic behaviour of complex systems. The idea underlying hybrid simulation is to combine a physical hardware, representing one part of the dynamic system of interest, with a numerical model representing the remaining part of the system. The interaction between the hardware and the numerical model is established by a suitable testing apparatus and a real-time computing facility.

Hybrid simulation can be applied to the study of pantograph-catenary interaction considering the pantograph as the hardware part of the system which is interfaced to a numerical model of the flexible catenary: as shown in Figure 3, the force generated by the physical pantograph at the contact strips is measured (blue line) and is used to compute in real time the dynamic displacement of the contact wire at the points of contact with the pantograph according to a numerical model of the flexible catenary; the displacement (red line) is applied on the pantograph head by one or more actuators (in black in the figure).

The advantage with respect to pure numerical simulation is that modelling errors related with the modelling of the pantograph can be avoided. These errors are typically caused by neglecting or simplifying non-linear effects (due to e.g. friction, backlashes, kinematic non-linearities) and flexibility effects in some pantograph components (frame, contact strips). At the same time, when compared to line testing, hybrid simulation is much less demanding in terms of the experimental work entailed, enables the investigation of innovative solutions such as active pantograph control without the risk of causing harm to the railway infrastructure and allows to perform investigations under repeatable conditions e.g. eliminating the effect of environmental factors.

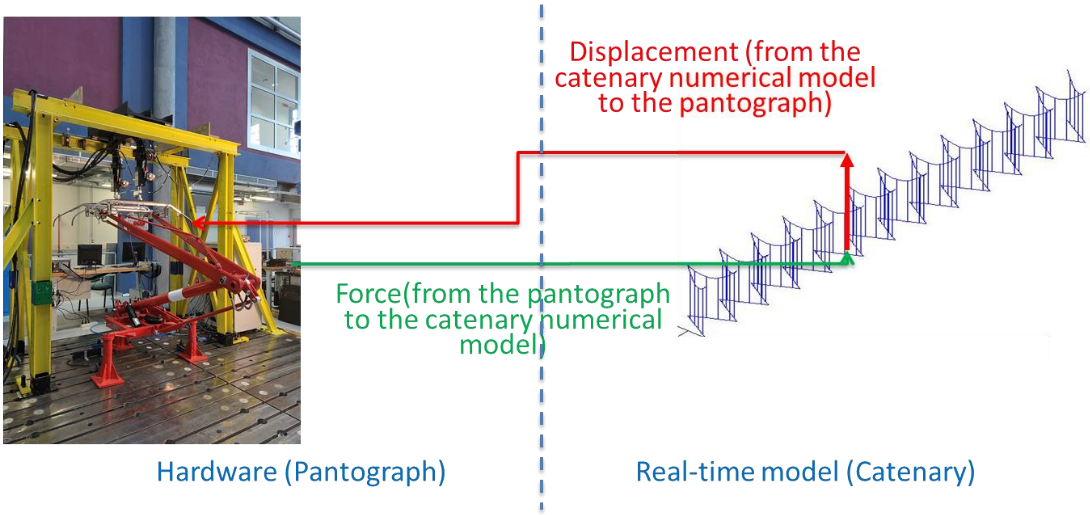


Figure 3. The concept of hybrid simulation of pantograph-catenary interaction

Hybrid simulation of pantograph-catenary interaction was originally proposed by Zhang et al. at the State Key Laboratory of Traction Power of Southwest Jiaotong University [38,39], using a linear model of the catenary based on modal superimposition. A refinement of this approach was provided by Resta et al. [40] by considering the effect of dropper slackening in the real-time model of the catenary. Facchinetti and Bruni [41] further refined the method by introducing the independent actuation of the two collector strips and by considering the effect of the stagger in the contact wire. Also in [41] the accuracy of the hybrid simulation approach is for the first time assessed by means of extensive comparison with line test measurements. The use of hybrid simulation for the design of overhead lines for very high speed (360 km/h and above) is discussed in [42] and compared with an approach based on 'pure' numerical simulation.

One main line of development for hybrid simulation deals with improving the control strategies of the testing apparatus realising the interaction between the physical pantograph and the virtual catenary. In [43] Stoten, Yamaguchi and Yamashita propose the Dynamically Substructured

System as an alternative to standard hybrid simulation, providing enhanced stability and robustness against uncertainties in system's parameters The method is applied to a so-called 'quasi-pantograph' i.e. a mass-spring system whereas the catenary is considered as a linear single degree of freedom system with time varying stiffness. In [44] Schirrer et al. propose an integrated impedance control strategy capable of compensating for the phase lag introduced by the control unit of the testing apparatus. The synthesis of this controller is formulated in terms of a linear model predictive control and hence is, in strict sense, not compatible with considering the non-linearities implied by dropper slackening and contact loss between the pantograph and the contact wire.

Another subject of present research is concerned with improving the accuracy of real-time models of the catenary. Facchinetti, Gasparetto and Bruni in [45] considered a class of models based on modal superposition and assessed the effect of changing the number of modelled spans and the number of modal components used to describe the vibration of the contact and messenger wires in view of finding the best model compatible with real-time simulation. In [44] an Eulerian model of the catenary, i.e. described in pantograph-fixed coordinates, is proposed. The model includes boundary absorbing layers to reduce wave reflection of waves at its boundaries. In this way, the computational effort required to solve the model is kept small enough to enable real-time computing and at the same time the motion of the catenary can be described to a good degree of detail. This approach however neglects dropper slackening, which is a major effect in pantograph-catenary dynamics. In S. Gregori et al. in [46] the numerical integration of the catenary equations of motion is decomposed in an "offline stage" and an "online stage". In the offline stage the time-step response of the contact wire and messenger wire to unit loads applied at discrete positions along the contact wire and at the dropper ends are calculated and stored. In the online stage the pre-calculated responses are used to reduce the number of dynamic equations to one for each pantograph plus one for each dropper, resulting in a computational effort compatible with real-time simulation. This method fully accounts for dropper slackening, whereas the catenary is modelled using the Finite Element method according to the Absolute Nodal Coordinate Formulation, thus allowing to represent in detail the geometry of the catenary, including the actual non-rectilinear shape of the messenger wire. Although this method has not been used yet for hybrid simulation, it looks as being well suited to provide a good balance between accuracy and computational effort.

4 Testing and qualification of pantographs and ocl

4.1 Generalities

The qualification (or homologation) process of a pantograph or of an OCL is a complex process, involving technical and managing issues and composed of several phases, from design to laboratory testing of the pantograph, simulation of pantograph-OCL dynamics in order to demonstrate the feasibility of the operation, and finally the testing of the pantograph on the rolling stock, in a series of trial tests. The aim of qualification is to ensure that the operation of a pantograph or of a OCL will take place regularly and without negative effects on OCL and rolling stock maintenance.

Qualification may take place at national level, applying national rules and standards, or at international level, e.g. applying TSI specifications [47] recalling proper EN/IEC standards [48-50]. The aim of the TSI process, strictly valid for the European network, is to assess the capability of a TSI-compliant pantograph to run under different TSI-compliant OCLs, and vice versa. In both cases the assessment involves mechanical and electrical issues. Considering line tests, with particular reference to qualification process, the following parameters are usually taken into account:

- mean contact force exchanged between pantograph and OCL as a function of train speed, this is related to the uplift of the OCL (especially under suspension, see point below). It is worth mentioning that current TSI provide a limit to the mean contact force up to 320 km/h. For higher speeds, national rules are applied or need to be established. In a recent qualification, the possibility to operate the pantograph setting a constant upper threshold for the mean contact force, from 320 km/h to 360 km/h, was analysed through simulations and verified with line tests [51];

- OCL uplift at suspensions, this is an exclusive mechanical issue related to the safety margin with respect to the engagement of the stagger arm by the collector that is passing by;
- dynamic component of the contact force exchanged between the collectors and the contact wire. This has to do with the mechanical and electrical issues involved in the electrical power transfer from the OCL to the drives of rolling stock's motors. Too high contact force may induce local mechanical damage on the OCL, whereas excessive occurrence of low values of contact force correspond to continuous sparking and arcing that causes electrical-related wear on collectors and contact wires, and disturbance to the signalling system or to the drives of the motor;
- percentage of contact loss, that represents the occurrence of arcing revealed during the pantograph collecting periods. At TSI level the contact force dynamic variation and the percentage of contact loss measurement are addressed as alternative quantities for the assessment of current collection.

4.2 Contact force measurement

The contact force between pantograph and catenary is directly related to the quality of the current collection. It is usually indirectly measured as the sum of the following three terms [52-54]:

- the forces acting between each collector and its suspension, measured by load cells mounted between each collector and its suspensions (see Figure 4);
- a term compensating the inertial effects in the collector strip, measured by two accelerometers located close to the load cells (Figure 4);
- a term compensating for the mean aerodynamic lift forces acting on the collector strips. This last contribution becomes important only above 150 km/h and is obtained by means of line tests performed on a restrained instrumented pantograph (Figure 5) in a wind tunnel or in the line.

The force measuring system described above is not free from drawbacks: the frequency band of the measure is limited to 20 Hz, since the compensation of inertial effects considers the collector as a rigid body. Moreover, the force transducers become part of the structure and must therefore ensure sufficient mechanical strength, generally conflicting with the sensitiveness required for the range 0÷500N typical of this application, and the impact of the transducers to the behaviour of the pantograph in terms of mass and aerodynamic effects is sometimes not fully negligible.

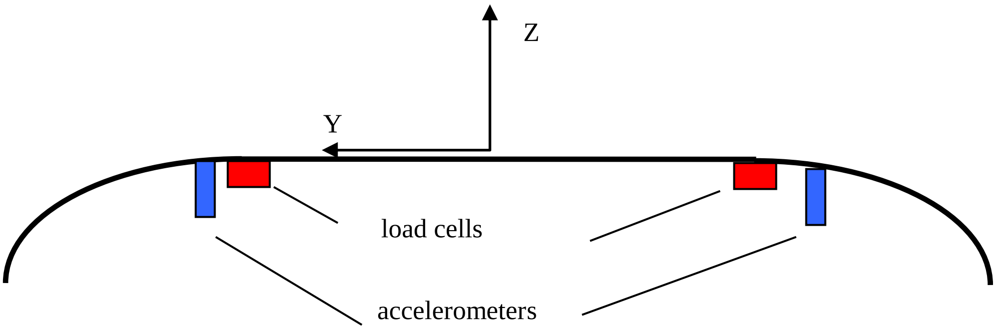


Figure 4. Sketch of the contact force measurement setup.

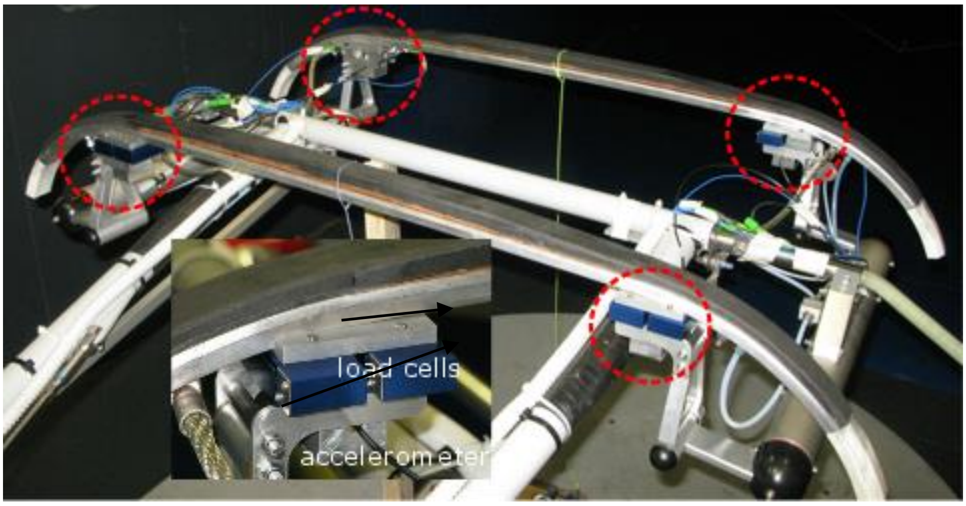


Figure 5. Example of instrumented pantograph for contact force measurement.

An alternative measurement setup is the one with strain gauges directly installed on the connection between the collector strip and the frame of the collector, as reported in [55], considering the contact force as proportional to the strain in such locations.

All the above described measurement setups are based on sensors requiring electric power supply: for the pantograph-catenary application this is problematic given that the pantograph works under high voltage. To guarantee the safety of the whole system, the most adopted solution features the use of a pack of batteries safely secured on the roof of the vehicle, nearby the pantograph. In addition, a second problem can arise: in order to ensure full electrical insulation, all the electrical signals outputted by the sensors must be converted into optical signals by means of converters and transferred to the data acquisition system (usually inside the vehicle) using fibre-optic cables. These signals then can be acquired directly or converted back from optical to electrical signals with other converters and sent to the acquisition board ([56]). To avoid problems related to the power supply of sensors and to the electrical insulation, in [51] and [57,58] optical load cells and optical accelerometers are proposed instead of electrical sensors. Optical sensors benefit from being intrinsically electrically insulated and insensitive to electromagnetic disturbances. Moreover, they do not need any electric power supply. These features make the optical sensors very suitable for the use on a pantograph and make the measurement setup very easy and with very low impact with respect to a traditional measurement setup.

In some application, as reported in [59,60], in order to simplify the measure setup, fibre optic sensors are directly connected to the collector strip and used to measure strains due to the interaction between strip and wire. This relatively simple and robust measuring set-up can be installed on pantographs used in commercial service and hence used for monitoring aims, see also Section 5.

The future developments of set-ups for contact force measurement are addressed to overcome the frequency limit of 20 Hz [61]. In any case, to this aim it is mandatory to consider collector deformability [62].

4.3 Contact loss detection

The standard method for the contact force measurement unavoidably modifies the original geometry and mass of the pantograph collector and its suspension, even if the measuring set-up is designed paying particular care to produce the minimum impact on the pantograph. An alternative method to evaluate the current collection quality is to detect contact losses through the observation of electrical arc generation. As reported in [63,64], the method is not invasive and is based on the optical measurements of the duration of ultraviolet emission due to electric arcing. The optical method can be used for both a.c. and d.c. current systems, while just for d.c. current system a method to detect contact loss based on the measurement and analysis of pantograph voltage drop is proposed in [52].

4.4 OCL motion

The analysis of pantograph-catenary interaction is generally completed by measuring catenary motion. In particular, the analysis of contact wire vertical uplift under the suspension (Figure 6) allows to verify the effect of pantograph load on the wire and to assess the safe and correct interaction between the pantograph and the catenary.

In [65] a dedicated wireless device is developed and proposed to measure wire accelerations at any location of interest, enabling to analyse/assess the motion of the OCL.

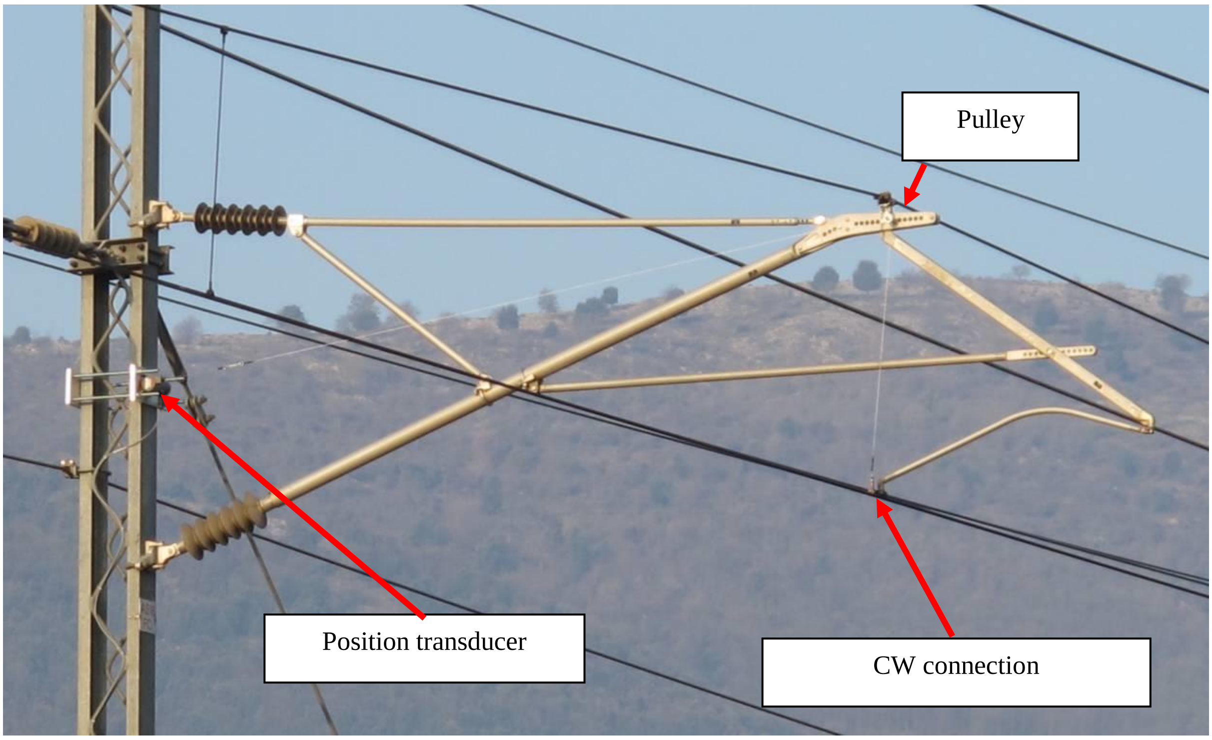


Figure 6. Example of contact wire uplift measurement.

5 Damage, condition monitoring and fault detection

Regularity of traffic operation is nowadays a highly mandatory issue for any railway network at international, national, regional or local level. The effect of traffic disruption can be costly in terms of lost hours of operation and impact on people's mobility. From this point of view, rolling stock and infrastructure maintenance is a key issue for maintaining the required regularity of train operation.

In the case of the pantograph -OCL couple, a failure of one of the two subsystems may have in the worst case a catastrophic consequence on both, the failure on the OCL being much more impacting on traffic disruption.

a)

b)

Figure 7 a) worn srface of a contact wire; b) worn thickness of a carbon contact strip.

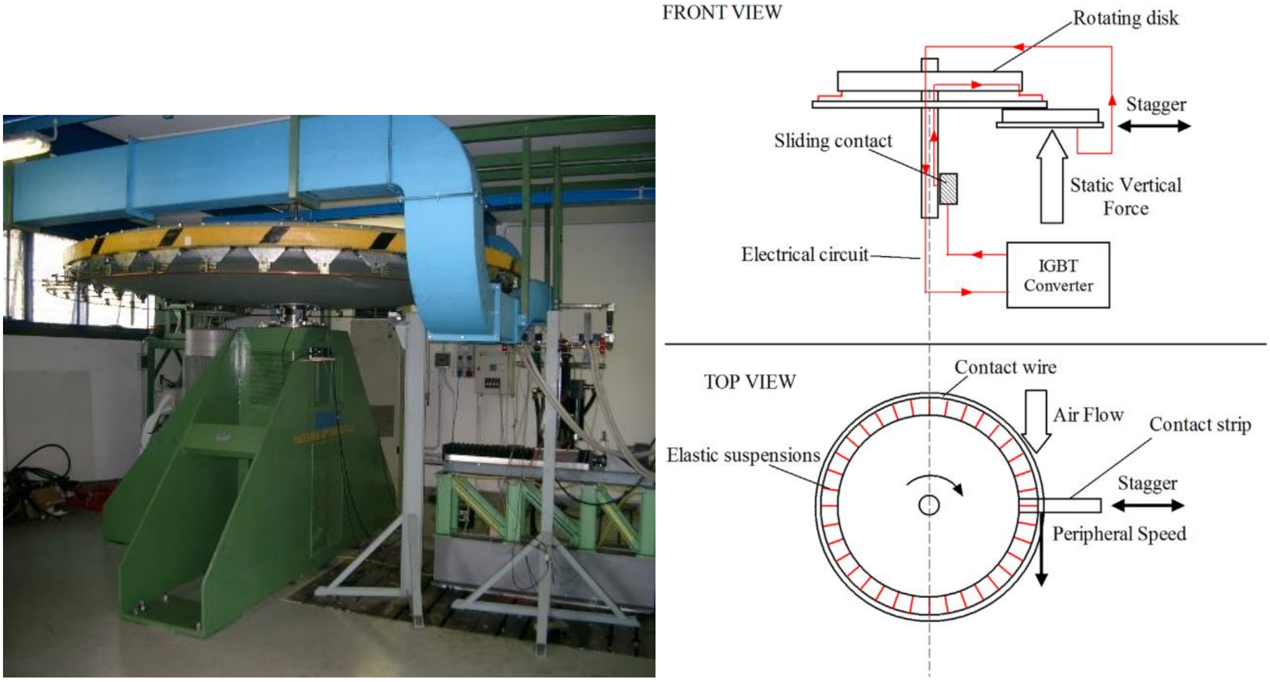


Figure 8 Picture and schematic views of the test bench developed at PoliMi ([71,75-77]).

One aspect of maintenance is related to wear phenomena which affect pantograph collectors and the contact wire (Figure 7). Researches in this field are aimed at the reduction of wear levels on both collectors and wires, to decrease life cycle costs. Some test benches (Figure 8) were developed to reproduce and to study the combined electro-mechanical phenomena occurring at the contact between collector strip and contact wire. Current intensity, mean contact force and arcing are generally recognized as mutually influencing factors in most studies performed. In particular, the reciprocal influence of mechanical and electrical wear is discussed in [66,67], while the effect of arcing on the wear of collectors and wires is analysed in [68,69], introducing the electrical discharge energy concept, and in [70,71] considering a.c. current collection. The influence of different types of contact wire and collector strip material on the wear is investigated by different researchers: pure carbon contact strip in [72], copper impregnated carbon strip in [68], iron based strip in [69], special sintered materials in [73] and reinforced carbon composites in [74] are just some examples. Finally, a procedure to extend laboratory data to operating conditions is proposed in [75-77]. In these papers, a numerical model for surface wear is introduced and used in combination with a method for the numerical simulation of pantograph-OCL interaction to estimate the wear rate of contact strip and contact wire.

The continuous increase of operation speed led some researchers to investigate new aspects related to OCL damage, as in [78,79] where fatigue problems in the contact wire are discussed.

To evaluate the correct actions to maintain the OCL, several means and approaches are available:

- visual and manual inspection (f.i. contact wire thickness verification), performed on regular time base. This activity is carried out mostly at local level, and its effectiveness is somehow depending on the skill and organisation of the local maintenance crew;
- measurement of contact wire (CW) geometry (vertical and lateral position) and thickness, using special inspection vehicles or trains. In this second case, rather sophisticated transducers are used to measure directly the geometrical parameters of the contact wire, in relationship with the location along the line. Depending on the class of the line (local, regional, high speed) the inspection is carried out at time intervals ranging from two months up to one year. Such systems are run by a skilled crew who manages the overall measurement process, and the results are analysed by specialised teams belonging to the maintenance management structure of the infrastructure manager;
- a new emerging option is to use commercial trains equipped with simple transducers (typically accelerometers) and to use the dynamic response of the pantograph as an indicator to detect defects along the line, or to assess the general OCL’s status in terms of contact wire vertical irregularity [80]. The use of commercial trains allows a daily data flow, and is the

prerequisite for the development of Condition Based Monitoring techniques, off-line trend analysis and Condition Based Maintenance.

In CBM systems the acceleration of the collector is typically used [81-83], since it is highly related to the contact force [81], both in terms of peak values and standard deviation. The issue of electrical insulation of sensors, together with the additional problem of using an easy-to-maintain measurement set-up, comes into play to develop a system suitable for installation on commercial-service trains. Optical accelerometers were especially developed for this application [81]. The loss of information inherent in the use of a set-up measuring only accelerations, instead of one also including the contact force measurement can be compensated by the larger amount of data acquired from several trains running under the same line. A cross-reference analysis of the data from different trains allows strengthening the identification of local and distributed defect of the OCL. Moreover, the comparison of different trains (and hence pantographs) on the same line enables to isolate those pantographs that are not in standard maintenance condition, so excluding their data for the analysis, and, at the same time, lead them to maintenance to restore their standard condition.

One main difference between CBM approach and the standard approach based on specialised inspection train is the far larger amount of acquired data, in terms of frequency of inspections and number of trains that acquire such data. If on one hand the availability of more data allows performing a more robust analysis, on the other hand it poses problems in terms of data management. To overcome this problem, a real-time processing of the data on-board train is generally proposed. Suitable algorithms allow reducing the large amount of raw data to a manageable, but still significant, set of parameters representing the status of the line [81].

To drive maintenance activities, the above mentioned CBM indexes (synthetic parameters) must be related to time stamp, GPS coordinates, or milestone position along the line. The latter can be evaluated on-board train when performing real-time analysis, and on-going research and experimental activities are nowadays aimed at improving the accuracy of algorithms and hardware for train positioning. This set of data must then be stored in a way side server, which enables further comparison with previously acquired data (trend analysis), to localise the defect, and to set the date of a damage event. The comparison between daily monitored situation and reference data will allow enhancing the detection of defects and the analysis of their long-term development, as well as to reveal sudden changes in the status of the line and take proper countermeasures before a serious failure occurs.

Finally, it should be mentioned that also other techniques have been proposed for the monitoring of the pantograph-catenary system, such as infrared camera to detect the temperature along the strip [84], and CCD and digital cameras [85,86] to infer relevant aspects regarding the status of pantograph and overhead line condition.

6 Experimental and computational aerodynamics

Pantograph and overhead line aerodynamics is responsible for affecting the contact force between the pantograph and the contact wire, both in terms of average value and dynamic variation [87-89]. This section deals with aerodynamic forces acting on the pantograph, the issue of wind effects on catenary having already been addressed in Section 2. When evaluating the pantograph performances for train speed higher than 200 km/h, aerodynamic forces on pantograph need to be considered, both when performing numerical simulations or when adopting experimental approaches.

The major aerodynamic effect is related to mean drag and lift forces acting on the moving parts of the pantograph, which affect the mean value of the contact force adding their contribution to the uplift force exerted by the pantograph raising mechanism at the bottom of the articulated frame (normally an air spring) [88,90]. This effect, usually addressed to as *aerodynamic uplift*, is dependent on train speed, pantograph working height [91] and orientation [92,]. Modern pantographs have indeed an asymmetrical geometry generating different aerodynamic uplifts in the two orientations in which they can operate. Moreover, the aerodynamic uplift varies when the pantograph enters a tunnel, due to the increase of the velocity of the relative flow [94]. Attempts to balance the aerodynamic uplift by means of aerodynamic spoilers were made in order to guarantee operational stability, but this was not trivial considering that it is very difficult to optimise the spoilers for both pantograph orientations. Therefore, in recent years, the regulation of air-spring pressure as a function of train speed and pantograph orientation has been proposed as a means to compensate for the aerodynamic uplift and to guarantee the best performances in both running directions and at all speeds [15].

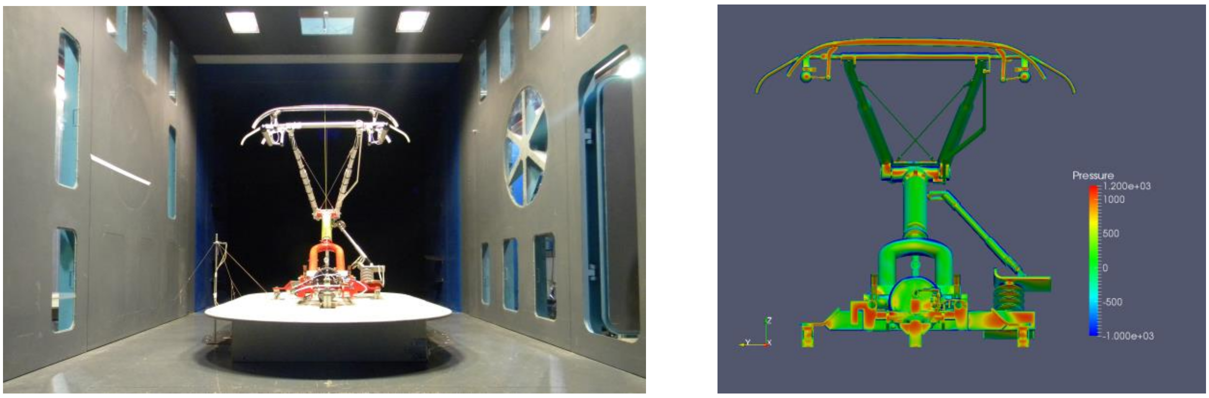
When pantographs with two independent collectors are adopted, aerodynamic steady forces can also generate an unbalance between the mean contact forces of the front and rear collector [87,92], with a negative outcome on power collection and a non-uniform wear of the two strips.

Aerodynamic non-stationary phenomena also influence the performance of a railway pantograph, and can be divided in two groups, related to the turbulence of the incoming flow and to vortex shedding. The presence of recesses, coach separation, electrical insulators, switches and other components installed on the train roof generates a turbulence wake, whose frequency spectrum is likely to excite the pantograph structure also within the frequency range set by international standards for the evaluation of the quality of current collection (0-20 Hz in Europe) [50,87,89]. In some cases, the turbulence can be even generated by pantograph components, such as the upwind collector or the air spring placed at the bottom frame, with the consequence that the rear parts of the pantograph are immersed in the turbulent wake.

Vortex shedding occurring in the wake of pan-head and collectors [96] should also be considered as a relevant issue, since it introduces very high-frequency excitation which not only has an impact on aerodynamic noise [97], but can also worsen the current collection quality, by exciting collector flexural modes of vibration and increasing the level of arcing [62].

Many research works have investigated the possibility to reduce the impact of aerodynamic effects on the quality of current collection. Several of them consider the problems due to average forces [95,98,99] and few consider non-stationary phenomena [100], mainly in relation to aero-acoustic issues [99,101]. At present, only average effects are regarded when evaluating the contact force variability, both in technical and scientific communities, as well as in EU international standards. The topic related to the frequency content of the incoming wind turbulence and its interaction with the pantograph structure is not much treated in the literature, either from experimental or numerical point of view.

Experimental on-track tests are still the main instrument not only for the evaluation of pantograph aerodynamic performance during the homologation process, but also for the fine-tuning of the best design solutions. Wind tunnel experimental tests (Figure 9a) are a powerful tool, since they allow to assess pantograph aerodynamic behaviour for several test configurations, architectures and design solutions under controlled flow conditions, but their drawback consists in the difficulty of reproducing the actual boundary layer of the train roof, and the turbulence conditions of the wind flow. In [102] the Authors point out the importance of the boundary layer reproduction in determining the uplift force in wind tunnel. They propose an effective technique to develop a boundary layer with similar characteristics to the one preliminary measured on the real train, which needs anyway, again, on-track tests to be tuned and validated.



a) b)

Figure 9 a) full-scale pantograph under test in a wind tunnel; b) example of CFD results in terms of steady state pressure over pantograph elements.

Computational fluid dynamics (CFD) does not yet represent a mature field for the evaluation of aerodynamic effects on pantograph contact force. CFD simulations have been performed in literature mainly focusing on the pantograph head and collectors model, in order to study drag and lift forces on these components [87] and acoustic emission [97,98,101,103]. Regarding the possibility of estimating aerodynamic forces on the entire pantograph, some authors have developed CFD models of a full-scale pantograph in a domain representing only the part of the carbody roof close to the pantograph [104], or CFD models of a pantograph installed on a full-scale train [105,106]. In [107], a full-scale pantograph is tested in a wind tunnel and the experimental results are compared with those of CFD models (Figure 9b). However, to the authors' knowledge, a complete validation of the CFD model against experimental results on a full-scale pantograph in wind tunnel and on a full-scale train became available only in the very last years in [92,93], in which a procedure for the numerical evaluation of the aerodynamic uplift is developed, based on CFD results and the application of the virtual work principle.

7 Active pantographs

Active control of pantographs has been considered as a possibility to improve current collection quality for a long time [108-109], especially for high speed applications, with the aim of reducing contact losses and contact force variability. The adoption of active control appears in principle promising to solve interoperability issues, considering that the same pantograph may interact with different catenaries and a comprehensive optimisation of the interacting passive systems is thus not feasible.

Several studies can be found in the literature, but most of them are limited to the proposal of control strategies and to the theoretical or numerical verification of the achievable performances. Only in few documented cases, these studies came up to the realization of active pantograph prototypes, verified through laboratory experiments [110-113] or in line tests [114].

The proposed solutions can be classified on the basis of the actuation principle or of the adopted control strategies. Considering the actuation principles, the actuators for applying the control action are usually considered to operate in parallel to the passive system rather than to completely replace pantograph components, in order to keep the possibility to operate in case of failure of the control system.

The control action can be applied on the articulated frame (Figure 10a), in parallel with the collector head suspension (Figure 10b) between the collectors and the articulated frame, or directly on the collectors (Figure 10c).

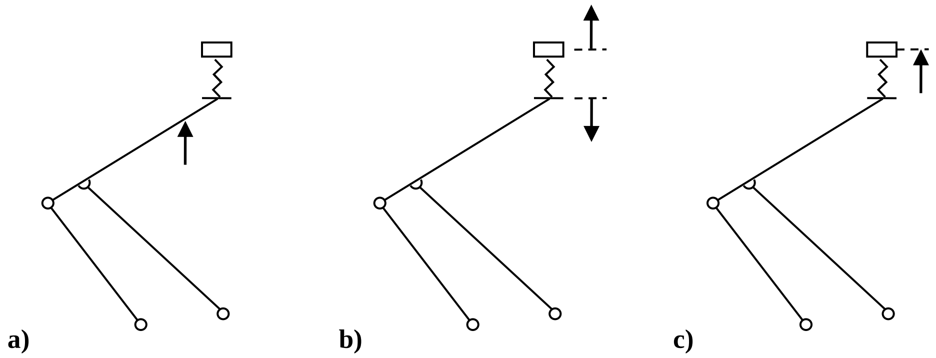


Figure 10: Actuation principles for pantograph active control: a) control action on the articulated frame; b) control action in parallel with the head suspension; c) control action applied directly on the collectors.

The first configuration is the simplest and has the advantage that there are no strict limitations to the size, power, mass and kind of actuator (pneumatic, hydraulic or electric), since the actuator can be placed directly on the vehicle roof. The pneumatic bellows equipping the pantograph for the raise/lower function and for providing a constant preload can be directly regulated by pneumatic valves to achieve a simple preload regulation, as done on the TGV fleet in France [115] or on the ETR500 and ETR1000 fleets in Italy [15], or to control the slow dynamics of the articulated frame [110,114,116,117]. As possible alternatives the introduction of an electric torque motor between the lower arm of the articulated frame and the vehicle roof is proposed in [118], the use of an hydraulic actuator in parallel to the pneumatic bellows of the articulated frame is reported in [6] and also adopted on a prototype in [113], whereas a wire actuation system connecting the extremity of the upper arm and actuated by an electric motor mounted on the vehicle roof is used in [111]. The main drawback lies in the limited bandwidth that can be achieved (up to 1-2Hz), on account of the filtering action introduced by the head suspension [119,120].

The second configuration, with the control action in parallel to the head suspension, is more effective for the control of the medium frequency range (up to 20Hz) but imposes limitations to the size and mass of the actuators that are placed in correspondence of the collector head suspension, thus increasing the overall mass of the pantograph. The possible implementations strongly depend on the solution adopted for the head suspension. The possibility to adopt a hydraulic actuator in parallel to the head suspension is reported in [6]. The adoption of a linear electric motor in parallel to the linear springs of the head suspension is considered in [118], while a torque motor is proposed in [120] on account of the different configuration of the head suspension. In [110,114] the head suspension consists of two torsion bar springs and the active control is introduced using two pneumatic actuators placed beside the two torsion bar springs.

The last configuration, with the control action directly applied on the collectors, is the most difficult to implement. Yet some possible solutions have been proposed, like the adoption of a wire actuation system connecting electric motors on the roof to the collectors [111,121,122] or the use of a movable wing placed just below the collector [123], driven by an electric motor and introducing a control action in the form of aerodynamic lift force.

Obviously, the different actuation configurations can be adopted at the same time, as described in [6,110,114].

As far as control strategies for the active pantograph are concerned, the proposed solutions can be divided in two macro-categories, i.e. those that consist in controlling directly the contact force and those where active control is used as a means to modify and improve the dynamic behaviour of the pantograph.

As far as contact force control is concerned both classical control techniques and modern control techniques were proposed. Contact force feedback with a PI regulator is investigated and its effectiveness proved in [121] considering a simplified model of the catenary and in [120] considering a detailed mathematical model of the pantograph-catenary interaction and of the electric actuation. PID adoption is considered in [124,125] and in [126], with the addition of a notch filter and particle swarm optimisation technique. In [110] the control system is made of two stages, one on the pneumatic bellows for slow dynamics and the other in parallel to the head suspension, both characterised by classical controllers. Considering modern control techniques, many different approaches can be found in literature, including but not limited to sliding mode control [122] and fuzzy logic [127,128].

It is worth remarking that all these strategies require either the direct measure of the contact forces (using the measuring set-ups described in Section 4) or an estimate of this quantity. In this respect, the adoption of an Extended Kalman Filter is proposed in [129] and verified with experimental data in [130]. An algebraic observability approach is considered in [131], while a sliding mode observer is proposed in [132].

A possibility to overcome the need for contact force knowledge is to use a different strategy for active control, aimed at modifying the dynamic behaviour of the pantograph. In this regard, optimal control has been considered by different authors [133-136] as a means to improve pantograph response. As an alternative, an approach based on the concept of mechanical impedance simulation is propose in [113], where the control action is used to emulate the behaviour of a desired mechanical system, which is not realizable using only passive components. In [137] sliding mode control is used to improve the mechanical impedance of the pantograph head and the approach was verified considering also the presence stochastic wind.

A direct comparison of the surveyed control strategies and of their effectiveness is extremely difficult, since they were applied to different pantographs and their evaluation was performed by means of different numerical models, characterised by different complexity levels (e.g. considering or not the control actuator dynamics).

As already mentioned, only a few proposed active systems have reached the prototype stage, so that further research is needed in order to verify the possibility to actually implement the suggested control strategies and to demonstrate their actual effectiveness in improving current collection quality.

8 Conclusions

This paper presented an overview on issues related to pantograph-catenary dynamical interaction. These can be summarised in the remarks listed below.

(1.) The numerical simulation of pantograph-catenary dynamic interaction is nowadays a mature approach for the design and prequalification of an overhead equipment. In order to be effective for the entire design of a OCL from the mechanical and dynamical point of view, also the singular sections and transitions need to be considered in the model. Future developments in this field are represented by the analysis of environmental effects (e.g. wind, temperature) on the motion of the OCL and hence on its interaction with the pantograph.

(2.) Despite being a relatively new approach to the study of pantograph-catenary interaction, hybrid simulation has been shown already to provide a degree of accuracy comparable to the one of 'pure' numerical simulation. Further important enhances to this technique are expected from the development of efficient methods for the real-time numerical simulation of complex catenary models and of course from the improvement of real-time computing hardware performances.

(3.) The simulation of pantograph-catenary dynamic interaction coupled with models of wear and fatigue in the contact wire can be used to establish reasonable parameters for the evaluation of life cycle costs of the OCL. Similar methods can also be used to optimise costs related with the maintenance and replacement of collector strips.

(4.) The improvement of methods for measuring the pantograph – OCL contact force is one important challenge related with the testing and qualification of new pantographs and catenaries. Future research needs in this area are concerned with extending the frequency range of the measure beyond the present upper limit of 20 Hz. Furthermore, the use of innovative sensors based on fibre-optics is a very promising field of research.

(5.) Line measurements of pantograph / OCL vibration and of the contact force are also relevant to the continuous monitoring of the OCL and with the implementation of Condition-Based Maintenance. In this regard, present and future research topics are concerned with developing robust and cost-effective measuring set-ups and with the analysis of measured data. The use for continuous monitoring of train fleets operated in commercial service opens new scenarios but requires the use of suitable ‘big data’ techniques.

(6.) Pantograph aerodynamics is extremely important in very-high speed applications. At present, the aerodynamic optimisation of pantographs is mostly carried out by means of experiments. It is possible that in the future some part of this development will be undertaken using computational fluid dynamics methods, but this requires a further enhancement of CFD techniques.

(7.) Finally, active pantograph control can be used as a means to improve pantograph-catenary interaction, e.g. operating at higher speeds pantographs under existing catenary that are possibly not optimised for very high speeds. However, there are few examples of demonstration of this technology up to the prototype stage and the effectiveness of active systems in improving current collection quality in real operation hasn’t been yet demonstrated. Research challenges in this area are concerned with developing actuation methods and active control strategies.

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Table 1: Caption

Figure 1: Caption