Simulation and Design of a High Speed railway Pantograph for Trenitalia S.p.A.

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Abstract

The paper deals with the design process undertaken for a proposed high speed pantograph oriented to the interoperability, developed in cooperation among Trenitalia SpA (Italian railway stock holder and manager) and three Italian universities. Aim of the work is the development of an optimized passive pantograph, in which the control of the contact force in the low frequency range can be also implemented. Several aspects have been taken into consideration in the design process, undertaken as a team work. Trenitalia leaded the overall coordination and the technical specification drawing, while Florence and Milan universities cooperated for the design and optimization respectively of the articulated frame and the collector head. Naples university studied the acoustical impact, in cooperation with Politecnico di Milano, where wind tunnel investigation have been performed on an existing pantograph. As a result, a complete pantograph has been designed and a first prototype has been made, to be tested in laboratory on a dynamic test bench. Subsequently it will be tested on line, with a proper measurement set-up, so that its performance can be assessed.

Introduction

Interoperability between different high speed railway systems involve the development of standardised industrial solutions able to operate under various technological standards. Trenitalia S.P.A. has spent a considerable amount of resources in the development of an innovative high speed pantograph able to work properly under different kind of overhead lines. Design and optimisation of this product involve lots of competencies that are usually owned by different subjects of railway and research sectors, so Trenitalia has decided to join its industrial experience with the know-how of different research groups chosen among those that have investigated various aspects of pantograph catenary interaction in past years. Politecnico di Milano deals with catenary design and simulation of pantograph catenary dynamic interaction [3]. In addition, the wind tunnel available in Campus Bovisa has been used to investigate some aerodynamic topics of the project. On the other hand, the University of Florence has a long tradition concerning the design of mechatronic systems and the mechanical optimisation of railway pantographs [1] through the combined use of tools for multi-body simulation and control system design. On the other hand, University of Naples is specialised in structural and material mechanics applied to various industrial applications and also deals with acoustic modelling.

In order to achieve the desired results a deep cooperation between different research groups was necessary so ITALCERTIFER S.P.A. was entrusted with the project management. Different activities were shared according to competencies and the capability of different groups to perform the assigned tasks within the decided time-scheduling. Also a common standardised platform for the exchange of simulation and design results was arranged in order to break traditional barriers between different scientific tools.

As a result, this heterogeneous group of researchers with different know-how and competencies was able in less than two years to completely design and optimise an industrial product able to meet Trenitalia specifications, so the production of a reduced series of prototypes for testing and calibration activities has started. The proposed solution is an asymmetric trolley with a reduced aero-acoustic profile and a five degree of freedom suspension system with independent sliding bows. Suspension system has been designed in order to optimise aerodynamic loads on sliding bows matching different air flow condition. The aim of this effort was to obtain a flexible system whose performances
were quite robust against aerodynamic disturbances due to lateral wind or to infrastructure interactions (for example tunnels). Finally the system is equipped with “a low impact” control system able to work as an active or a semi-active suspension on the articulated frame according different operating conditions. “Low impact” control systems means that the design was optimised in order to reduce industrial costs and increase reliability and diminish maintenance costs of the pantograph. This was a very hard task since the system had to be designed to be very simple, redundant and with reduced encumbrances in order to maintain the advantages of high optimized aerodynamic structures. In this work design methods, advantages and drawbacks of the proposed solution are shown and discussed.

Figure 1 Frequency response Function in terms of acceleration over force at the centre of a collector for 25kV.

Figure 2 First flexural mode of a typical of a collector for 25kV.

Overview on the general requirements of a pantograph from the dynamic point of view

The requirements of a high speed pantograph involve several aspects, some of which are sometimes conflicting each other. The main points that require optimization are:

- minimization of the masses of the structural elements in general, and the mass of the collector in particular. The latter are of high importance in the dynamics of the contact force, since they are
directly in contact with the catenary, and influence a broad frequency range, from droppers passing frequency (8-12 Hz, according to the train speed and droppers distance, usually around 7m) up to the first flexural modes of the collector. These frequencies (usually in the range 50-300 Hz), being the highest frequencies related to continuous sparking. Figure 1 shows as an example the Frequency response Function (FRF) of an existing collector for 25 kV, while the subsequent Figure 2 shows its modal shape for the first flexural frequency. As shown in the FRFs, the level of damping of the deformable modes is very low, in the range 0.1÷0.3% of the critical damping. It would be favorable to increase the damping up to 1%÷1.5%, so that the contribution of the higher modes could be lowered. This may be achieved sing, for instance, adopting metal matrix composite material [4], which show higher damping level than classical metallic materials, but for the present project this option has not been considered, due to the cost of this solution.

- Minimization of the aerodynamic impact (global and local) and related acoustic emission: this is related to the general architecture of the articulated frame and to the shape of the collector head. The choice for a single tube architecture for the upper arm (see Figure 3) follows from considerations on noise emission and aerodynamic drag on the pantograph [2].
- Structural frequencies of the frame, that should be higher than droppers passing frequency (about 12Hz), or at least dynamically uncoupled from the collector head motion in the range 8-15 Hz, both for vertical and for rotational motion of the collectors. A pure lateral mode of the frame is usually placed in the range 5-7 Hz, while two subsequent mixed flexural-torsional modes are present in the range 8-12 Hz. In the first the head shows the maximum amplitude with a combined lateral and rolling motion, coupled with a flexural torsional mode of the articulated frame, in the second is the knee of the articulated frame that shows the maximum amplitude.
- Minimization of the unbalance of the contact force between front and rear collectors of the head, which is caused by the lift and drag aerodynamic forces acting on the head, and on the individual collectors in particular. For this problem the effort concentrates on reducing the drag forces, but this is not easy to be implemented unless a special profile is adopted, or to optimize the kinematics of the head, placing the instantaneous center of rotation of the head close to the contact wire height, such as in [6].
- Possibility to include passive or active control at the base of the pantograph, mainly aimed at equalizing the dynamic behavior of the pantograph at low frequency range (span passing frequency) under different catenaries. This aspect is particular relevant for the interoperability. Main difficulties on this topic arise from the proper choose of the actuator (pneumatic or hydraulic), and in keeping it in a small room, due to the limitation in the available dimension at the base of the frame of the pantograph. The second capital topic is the control strategy, that if it is based on a closed loop on the contact force, is critical due to the uncertainties and high level of noise related to the direct contact force measurement.

Moreover all these goals should be reached with solutions that are feasible from the manufacturer point of view.

Figure 3 Single tube architecture for the upper arm (left) opposed to a frame architecture (right).
Technical specification

Technical specification have been delivered by Trenitalia as end-user [1], first of all according to the requirements of TSI, and also according to the experience gained from the experimental test that are carried out by the experimental unit of Trenitalia. Main topics are dimensions, such as collector shape, working height range, dynamic performances in terms of quality of current collection, sensitivity to aerodynamic actions and lateral wind, resistance to acceleration levels of 5g in longitudinal and 3g in lateral direction, lateral stiffness at the level of the head, required as 30mm of allowable displacement under a 300N force applied at the top of the pantograph. From the aeroacoustic point of view the request is a reduction of 5dB in the overall level, with respect to the existing ATR95 pantograph. Moreover it is requested the non stationary phenomena, typically due to local elements, should not appear in the speed range of interest. Other specification are set for what concerns the assessment of the requested performances.

![Figure 4 General flow chart of the design and verification process](image)

Design process and development of the structure of the pantograph

As mentioned in the introduction, several working units have been involved in the process of design and testing. In particular Trenitalia entrusted Italcertiferr for the role of management coordination, while it delivered the technical specification. University of Florence and Politecnico of Milan cooperated for the design of the structure of the pantograph, while University of Naples dealt with materials and acoustic impact prevision.

The general philosophy for the design was to obtain a structure that can easily undergo subsequent modifications, especially for the head and the collectors, so that future improvement can be implemented. Moreover the design aimed also at allowing set-up regulations, such as the vertical position of the collectors with respect to the head frame, or the possibility to modify the stiffness of the suspension simply changing the springs, but without the necessity of any structural modification.

For the structural design of the articulated frame and the collector head, first a kinematics optimization has been carried out, by means of proper codes such as Adams®, then a finite element analysis has been performed in order to check the mechanical strength and the value of the natural frequencies. In particular University of Florence developed the articulated frame, which is based on a single tube architecture. This choice has two main aims: the first is to minimize the global aerodynamic impact, considering that a differences of aerodynamic uplift due to the different directions are controlled by the air spring. The second aim is to deliver a proper flexural and torsional stiffness of the frame with an efficient shape, so that the expected structural coupled flexural-torsional modes have their frequency at about 12 Hz. As mentioned, the articulated frame has been optimized also from the kinematics point of view, so that the vertical trajectory of the head is as close as possible to a vertical straight line. In this way the effect, on the aerodynamic uplift, of the drag forces acting on the head, is cancelled.

As far as the head is concerned, the first aim was the reduction of the mass in direct contact to the contact wire. For this reason, an integrated structure for the collector has been chosen, that is a supporting structure made of an aluminum extrude, on which a graphite strip is connected. This enable a reduction of 35% of the mass with respect of the collector currently used, still keeping all the natural frequencies above the 50 Hz. The kinematics of the head has been designed so that the relative center of rotation between the head and the upper arm can be located in between the center of pressure of the aerodynamic drag
forces acting on the collectors and the contact wire. In this way, as already reminded, the effect of the longitudinal friction forces and drag aerodynamic forces, that usually cause an unbalance of the vertical contact forces, is minimized. The geometry has been previously calculated with a non linear planar scheme, and subsequently tested in the wind tunnel, on a model of the solution. The other innovative part of the pantograph is the application of passive and active control at the base of the articulated frame. This subject is considered in the following section.

Application of the control on the articulated frame

As mentioned in the introduction, the pantograph has been designed considering the possibility to implement a control on the articulated frame. Several type of actuators and control strategies have been investigated by means of preliminary simulations, choosing at the end an hydraulic actuator, that appeared to be the most effective solution from the point of view of dynamic performance. The main idea is to use the same component for the passive and the active mode.

In the passive mode, the value of the equivalent viscous damping is obtained by means of a bypass valve, that can be controlled so that the desired value of damping can be set.

A series of simulation of the dynamic interaction between pantograph and catenary has been performed for different speed and different types of catenary (C540 3kV, C270 25kV, SNCF), varying the values of the viscous damping of the articulated frame, so that an optimized value can be set for each type of catenary. This is particularly of interest for the case of double pantograph configuration for the second pantograph, that usually undergoes a higher vertical displacement due to the interaction with the motion of the catenary that follows the transit of the first pantograph.

Figure 5 shows the optimal value of the equivalent viscous damping obtained from the simulation, for the fist and the second pantograph, under the C270 catenary. The same calculation has been performed for C540 and SNCF-TGV catenary, obtaining different graphs. Tuning the damper by means of the by-pass valve, it is possible to adjust the proper damping value, according to the speed, first and second pantograph, and type of catenary.

The second aspect of the control is the implementation of a basic active control, acting on the articulated frame, aiming so at controlling only the very low frequency range, related to the span passing frequency, and eventually its second harmonic component. This limit the band of frequency to 2-3 Hz.

![Figure 5: Optimal value of the damping for the C270 catenary, for first and second pantograph.](image-url)
Figure 6: Contact force simulated for C270 catenary, for the case with control (red line) and with control (blue line).

Figure 7: Spectrum of the contact force simulated for C270 catenary, for the case with control (red line) and with control (blue line).
For the proper selection of the actuator, and the design of the control strategy, preliminary simulations with a simplified model of pantograph-catenary dynamic interaction have been performed, including the full dynamics of the actuator. Considerations about the air consumption, the frequency range required and the power requested, leaded to the decision to consider an hydraulic actuator. The dynamic model of the actuator has been then implemented in the full dynamic model of pantograph catenary interaction, so that a first stage of verification of the effectiveness of the proposed solution could be done. It is reminded that in the simplified model, based on a simple modal approach, the droppers are not considered, while in the complete catenary model, the droppers and their non linear effects are fully considered.

As an example, Figure 6 reports the differences in the simulated contact force for the standard case and for the controlled case, and the subsequent Figure 7 shows the corresponding spectral analysis. It can be seen that, as expected, the first harmonic components of the contact force are reduced in the controlled case, and on the other hand the behavior does not get worse at the frequencies related to the droppers.

Final remarks

A new pantograph has been designed by a team of universities co-ordinated by Trenitalia. The aim was an interoperable pantograph, that can incorporate a basic active control at the lower arm of the articulated frame, and that can be industrialised. A first prototype has been made, and the first test of laboratory follow soon.

References

[2] W. Baldauf, R. Blaschkó et al, Development of an actively controlled, acoustically optimised single arm pantograph, WCRR01