Design and development of an active suspension system for T-2006 Pantograph

L. Pugi, B. Allotta, F. Bartolini, M. Rinchi, A. Collina, F. Resta, G. Bucca, A. Facchinetti, R. Cheli
University of Florence, Florence, Italy; Politecnico di Milano, Milano, Italy; Trenitalia SPA, Firenze, Italy

Abstract

The authors of this paper have worked within a team formed by Trenitalia S.p.A., Italcertifer, and two Italian Universities (Università di Firenze and Politecnico di Milano) with the aim of developing a prototype of an innovative pantograph for Italian high speed lines. The focus of this paper is on innovative solutions proposed for the actuation system and on promising experimental results obtained during dynamic tests performed in various laboratories.

The proposed control strategy is based on the theory of impedance control [1], i.e. the simulation of “desired” mechanical impedance by means of the active control of a mechanical device: the controlled pantograph is able to emulate, within certain limits, mainly related to the need for maintaining system stability, the desired dynamic response of a “virtual pantograph”.

The advantages of the proposed solution are quite evident since force measurements or estimations are not necessary, improving reliability and reducing the costs of the active pantograph. Control design is also quite simple and robust against parameter uncertainties introduced by catenary modeling. Moreover, the proposed control-actuation strategy is quite general, since it is not constrained to a particular mechanical layout so, with very limited modification, it can be easily applied not only to the Trenitalia T-2006 prototype but also to other 2-stage pantographs.

Introduction

Improvement of current collection quality it’s a long term issue of railway engineering. As railway commercial speed increases, a better optimization of pantograph-catenary interaction is necessary to assure a good current collection quality. Several Authors have studied this technical problem in the past years; a lot of these have proposed [2,12] and studied the feasibility of active or semi-active suspension system applied to railway pantographs in order to improve current collection quality.

Heavy costs of experimental activities and harsh environmental condition to which is exposed a pantograph on train roof have represented serious treats that have often limited the feasibility of proposed solutions.

Authors of this work, learning from past experiences, have tried to develop a reliable prototype which is conceptually derived from existing passive pantographs installed on high speed trains as the example in figure 1.

Figure 1: a commercial passive pantograph (Schunk WBL 85) and its main components (nomenclature used in this work).

This prototype called T2006 has been designed as a traditional asymmetric pantograph with a very optimized mechanics in which the passive damper that usually smooth mobile frame oscillation is replaced by an active hydraulic actuator controlled by a real time system. The proposed actuator is in a relatively protected position and it is possible to assure a minimal protection from atmospheric...
conditions. This active hydraulic actuator can be also used to test active feed-back algorithm or impedance optimization strategies based on the emulation of variable actively controlled dampers. The pantograph prototype has been successfully realized according Trenitalia specifications[13] and it has been widely tested using experimental devices build up for first calibration by researchers of University of Florence and advanced laboratories present at the Department of Mechanics of Politecnico di Milano. In the following sections the main design stages and the results of research are discussed. In particular, the work is articulated according key points of the project:

- Mechanical Design
- Actuation and Control System Design
- Dynamic Response Testing
- Test in Politecnico di Milano Wind Tunnel.

Mechanical Design

In order to reduce the encumbrances and to respect the requirements of Trenitalia Specification [13] especially in terms of interoperability respect, a mobile frame solution with four bar linkages, as the usual asymmetric pantograph for high speed application (figure 2), has been used. Four bar linkage kinematical behaviour has been optimized by means of the use of the simplex method, according Nelder-Mead approach [14] implemented on a Matlab-Simulink model in order to assure a straight vertical trajectory of the head. This optimization criterion has been chosen in order to reduce mobile frame sensitivity to longitudinal forces applied to the head such as aerodynamic drag or friction between sliding bows and contact wires. In fact it can be easily demonstrated that a vertical trajectory of the head involves that the work of applied longitudinal forces is null. A force to which is associated a null or negligible work doesn’t affect the dynamic behaviour of a system that can be studied with classical mechanical methods such as Lagrange equations or virtual work principle.

Once mobile frame kinematics was optimized, authors decided to design the pantograph adopting a mono-tube structure very close to many pantographs installed on high speed trains in order to minimize mobile frame transversal section from an aero-dynamic point of view. A correct angular orientation of sliding bows with respect to the line has been considered very important to assure a good contact quality and to reduce the wear on the contact shoes and on the contact wire. In order to satisfy this second kinematical condition, a sophisticated solution, which is also adopted by Ansaldo ATR95 high speed pantograph, has been used. This design solution consists of an auxiliary bar (figure 2) which assures head alignment through a pin/cam constraint. The cam design is optimized using the multi-body code MSC ADAMS.

The head has been designed with double independent sliding bow suspension with five equivalent degrees of freedom in order to assure high capability of the system to follow line irregularities. Increased degrees of freedom assure lower equivalent inertia of sliding bows. The position of pitch rotation center of the position can be easily optimized with little modifications of head linkages. Thanks to this feature head rotations due to pitch torques caused by drag or friction forces can be easily compensated if the rotation center is aligned with the resultant of longitudinal forces applied to the sliding bows, as shown in figure 2.

The resulting structure of both mobile frame and suspension system has been optimized using FEM tool in order to reduce masses and to improve modal response. The pneumatic and hydraulic actuators used to control the dynamic behaviour of the system have been adopted instead of the air spring and dampers typically used on passive pantographs, respecting the severe encumbrance specifications imposed by Trenitalia in order assure the respect of clearances with surrounding infrastructure (figures 2 and 3).
Actuation and Control System Design

The placement of the pneumatic and hydraulic actuators in the lower part of the mobile frame makes easier the design giving the possibility to use standard industrial components with high reliabilities and affordable costs.

Both hydraulic and pneumatic actuators placed on mobile frame are driven by fast-response proportional servo-valves, as shown in the simplified scheme of figure 4. However, only the hydraulic actuator is used to compensate the dynamic behaviour of the pantograph, while the pneumatic one assures a precise static lift variable according operating conditions, as the actual train speed or the kind of overhead line. All the plant is designed in order to assure redundancy and a fault safe behaviour: if a fault occurs the pneumatic actuator works also as backup unit assuring the lift necessary for passive operations while the hydraulic actuator is turned in a passive damper by the automatic opening of an orifice between the two chambers, as shown in detail in figure 4. The orifice area can be regulated allowing to reproduce a wide range of different damping effect.

Electric insulation of the plant is assured by dielectric properties of the oil that is also used to provide the limited electrical power needed by sensors and signal conditioning devices.

The real time hardware used for the control and the diagnostics is located in a more protected position inside the vehicle. Signal exchange with sensors and actuators is assured by a galvanically insulated fiber optic links.

The pantograph is equipped with several sensors able to measure vertical and lateral forces applied on sliding bows. Accelerometers are integrated in the contact force measurement system in order to compensate inertial contribution of contact shoes, according typical scheme often used in literature [15-17] and wide diffused among different group of researchers. Sensor layout is completed by a wide
array of sensors used to measure kinematical behaviour (running position, speed, acceleration) of both sliding bows and mobile frame (figure 3).

Figure 4: simplified scheme of actuator plant and control hardware layout

The design of the control system able to regulate the system dynamic behaviour has been developed using the displacement sensors placed on the mobile frame and on the sliding bows suspension instead of the load cells, in order to have a cheaper but reliable solution. The contact force measurements by means load cells are only used on the prototype to quantify performance improvement introduced by the control system.

A wire actuator, shown in figure 5, able to impose controlled displacement force profile on sliding bows according RFI regulation[18], is used to identify the so called “apparent mass” of the pantograph which is defined as the reciprocal of the inertance function (1):

$$M_a(s) = \frac{1}{\dot{X}_a I(s)}$$

(1)

where:
- $M_a(s)$ = inertance function
- $F_c$ = Contact force applied to sliding bows
- $\dot{X}_a$ = Measured Acceleration of the application point

Identification tests are done with the pantograph working in passive mode. In this condition, the hydraulic system is switched off and the bypass orifice of the actuator is “opened”: the orifice area is the maximum available, so the equivalent damping is the lower possible (about 70 N/ms reduced to head).

Figure 5: simplified scheme of actuator plant and control hardware layout

Results reported in figure 5 show an equivalent inertia in the range between 3 and 20 Hz of about 15kg well under the prescribe maximum values from 40 to 25kg according different classes prescribed by regulation in force[18]. Higher equivalent masses have been measured at lower frequencies where the contribution of residual damping and friction effects of actuators and mobile frame inertia can’t be completely compensated by the deformation of sliding bows suspensions.
However measured inertia of sliding bows and their attachments to the suspension system is about 5-10kg (according different kind of contact shoes and calculation hypothesis), so there is a consistent quote of equivalent mass that can be imputed to interaction with mobile frame through the suspension system.

The proposed control system is an application of mechanical impedance control technique [1]: through kinematical measurements of suspension and mobile frame displacements the control system tries to cancel or simply reshape their contribution on the dynamic response of sliding bows in order to reduce equivalent mass of the pantograph, thus improving its capability to follow overhead line displacements. Improving pantograph inertance and mobility of the pantograph involves a better interaction with catenary, improving not only contact quality but also current collection and system reliability and maintenance.

In order to assure fail safe behaviour and obtain the desired behaviour, the hydraulic actuator is controlled with a sophisticated pressure/force control loop, able to produce a desired force, or to emulate a desired dynamic behaviour, for example an adjustable damper. Models used for control implementation, whose details are omitted in this work, are derived from literature [19,20,21].

In order to calibrate and then to evaluate control performances, authors have used imposed displacement test using the same wire actuator used for the identification of the equivalent inertia of the pantograph. The test procedure is the following: imposed sinusoidal displacements with known frequency and amplitude are applied to sliding bows; force applied by the actuator is measured, and lower values of measured force involve better mobility and inertance of the pantograph and then a lower equivalent mass.

After a first calibration stage, authors have been able to find a control system configuration near to the optimal control one, whose performances are described in figures 6, 7, 8. Figure 6 shows time history and spectral analysis of recorded force profile during an imposed displacement test at a frequency of 1.5 Hz with amplitude of ±2cm.

Results are compared with equivalent data obtained making the same test on the pantograph working in passive mode with control disabled and actuator orifice opened: benefit of the control system are quite evident: there is a big reduction of force oscillation without any dangerous phenomena of spillover at higher frequencies.

Further tests have been carried out in order to verify system performances with increasing level of fault of the sensor system. These tests were performed to evaluate how the system may work in case of minor or particular fault not detected by system diagnostics.

In the example shown in figure 7, the displacement sensors on suspensions are de-activated simulating an undetected fault condition: as the number of fault sensor increases, system
performance decreases. However the pantograph continues to work without any trouble of instability, thanks to the fault safe architecture and to the robustness of chosen control strategy.

Finally, in figure 8 a summarizing graphic of obtained results is shown and four different system configurations are compared in terms of standard deviation of actuator control force at various frequencies:

1)"Normal" and "Improved": in both the configurations the control system is full working; the only difference between the two states is a different setting of control parameters, corresponding to higher performances in "improved" configuration or to robustness in "normal" one.

2)"Degraded 4": a fault of all sensors placed on the suspension system is simulated. Fault diagnostic is not working, so the system has not recognized the fault condition.

3)"Fault": the system has recognized a fault condition so the pantograph is working in passive mode since the hydraulic actuator is switched off and the bypass orifice is open.

It's interesting to notice the general good performances of the system and its robustness even if the diagnostic of the system is not able to detect a fault condition.

This is mainly due to smart choice of nested position and force loops of the control system.

Further test have been performed with success also on the Hardware in the Loop dynamic test rig of Politecnico di Milano [22]. In figure 9 a picture of the prototype during tests executed on the test rig is shown.

Further improvements of the control system may consider the possibility to use only accelerometers as input for the control system in order to increase reliability and to reduce encumbrances. Authors have already made some tests obtaining encouraging results. However in this stage of research activities some troubles concerning stability of the control system in case of sensor failure or in particular working condition have aroused.

Tests on aero-dynamic Tunnel

The pantograph prototype has been also tested in the aero-dynamic tunnel of Politecnico di Milano in order to verify how aero-dynamic effects on pantograph in terms of lift and drag forces may affect force distribution on sliding bows and more generally to identify the system response from an aero-dynamic point of view. In particular, an analysis on the influence of sliding bows distance from the suspensions on the sliding bow force distribution has been carried out.

In order to measure aero-dynamic forces and torques due to aero-dynamic interaction with incoming flux of air, the pantograph has been placed on a floating platform constrained by means of an array of rods with force sensors, as shown in figure 10/a. The measurements provided by the force sensors and static and geometrical considerations enable to quantify the force components that are relative to the lift and drag forces and the corresponding torques.

On the pantograph two load cells connected between the fixed basement of pantograph frame and each sliding bows by means of tendon links enables to calculate the lift force acting on the sliding bows. This connection has been also used to provide the static preload on the pantograph which typically acts between during the pantograph-catenary interaction.

During the aero-dynamic tests both the configurations with the pantograph knee in front of the wind and vice-versa are analysed. It has been found that the better aero-dynamic behaviour of pantograph in terms of force distributions on the sliding bows is provided when the knee pantograph is in front of the wind. In this configuration the pantograph presents a neutral aero-dynamic behaviour. The second configuration the aero-dynamic effects give rise to an increase of vertical force on the pantograph.

The aero-dynamic tests have been also used to verify the influence of distance between sliding bows and suspension on sliding bow force distribution (figure 10/b). The suspension system has been modified in order to make possible a calibration and adjustments of the suspension geometry respect to the pitch rotation centre. Since the suspension system can rotate around the pitch rotation centre,
the longitudinal forces acting on the sliding bows due to the drag forces applied to bows and the friction forces that arises during the sliding contact between shoes and overhead line produce a pitch torque that influences the lift force distribution on the sliding bows. This phenomenon involves negative consequences such as non-uniform wear on the contact shoes and a deterioration of current collection quality. Therefore, this effect has to be avoided modifying the position of the pitch rotation that has to be near to the longitudinal force application point.

Making several aero-dynamic tests, authors have been able to find a configuration near to the optimal one, that enables an equal distribution of vertical contact forces between sliding bows. Figure 11 shows a comparison of the measured contact force distribution on the two collector, in terms of difference of contact forces between the front and the rear collector, for different suspension configurations, as a function of incident wind speed. It can be observed that configuration 2 allows to strongly reduce the influence of aerodynamic forces on contact force distribution. However it is difficult to define an absolute optimal solution, because this solution is sensible to the real operating conditions, such as the direction of incoming air flow that may be different from wind tunnel condition, for example for the effect of lateral wind or to secondary un-modeled flow due to train roof shape.

In order to increase the robustness of the proposed solution, rotation around the pitch rotation centre can be limited by introducing torsion springs on suspension rods able to produce a limited self balancing torque.

![Floating platform with load cells](image)

**Figure 10/a:** Floating platform with load cells

![T2006 Suspension system modified](image)

**Figure 10/b:** T2006 Suspension system modified to make possible calibration of suspensions relative position respect of pitch rotation centre and tendon links used to preload the system and measure lift forces

![Wind Tunnel tests](image)

**Figure 11:** Wind Tunnel tests, contact forces difference between the front and rear collector, for different suspension configurations.
Conclusions

Thanks to the cooperation between several groups of researchers a prototype of an innovative pantograph for high speed application has been completely designed. Research activities have produced both direct and indirect benefit:

1) In particular an innovative actuation and control system has been successfully tested showing the feasibility of a technical solution that can be also applied to other commercial products in order to improve their low and mid span frequencies (range 0-6Hz) response by re-shaping system mechanical impedance. The system is quite fail safe and it can even be made cheaper and more reliable for a larger production scale.

2) Aero-dynamic optimization of sliding bows and suspension system was a furthermore occasion to understand how little change in the system geometry may significantly improve load distribution between the sliding bows and to further investigate methodologies for system identification and optimization.

3) An indirect but significant result was also a massive cross-sharing of knowledge between different groups of researchers that usually work on different aspects of the same problem, encouraging and inspiring less conventional solutions and research methodologies.

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