Innovative solutions for active railway pantograph

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Abstract

Current collection’s quality is a critical factor for the development of high-speed railways. The dynamic behaviour of the pantograph-catenary system at high speed negatively affects quality and stability of the contact between the sliding bows and the wires.

Negative consequences of an insufficient current collection’s collection are well known among researchers: insufficient current pick up, wear and over-heating of sliding surfaces, high EMI, low electrical and mechanical reliability of the system. Several solutions were proposed in the past years to solve this problem.

In this paper the authors propose an innovative layout for an actively controlled railway pantograph. This kind of active pantograph should be used to control some variable, such as contact force between sliding surfaces, by using an array of actuators able to correct the dynamic behaviour of the pantograph-catenary system. The design of an innovative actively controlled pantograph has to respond to low-cost, reliability and harsh environment specifications.

Moreover, in this paper the authors propose a concept solution, the “overturning pantograph”, based on both main frame and sliding bow suspension’s innovative schemes. Tri-dimensional models of the pantograph have been developed by using various parametric CAD Systems. CAD geometry was exported in software tools for structural and multi-body-dynamical analysis using the Parasolid standard format.

Parametric features of CAD software and prediction capabilities of multi-body analysis tools have been used to iteratively find a sub-optimal solution.

Simulation results of the new solution and experimental data of a another type of controlled pantograph, previously developed, are compared and evaluated. The comparison shows feasibility and potentiality of the proposed solution.
1 Introduction

The design of a complex mechatronic system such as an actively controlled trolley involves many different aspects concerning dynamic behaviour of the system, regulator's synthesis, structural and modal analysis.

Communication between various computer-aided-design tools and researchers with different backgrounds is the key to improve efficiency and productivity of the work-team. In this paper the authors show how the application of concurrent design criteria has accelerated the development of the project that is still in progress.

The discussion will follow this order:
- Aim and specifications;
- Kinematical studies and verifications of dynamical properties;
- Dynamical test and optimisation on a virtual Test Rig;
- Conclusions and future improvements.

2 Aim and specifications of the project

2.1 Performance and Reliability of the system

Current collection system reliability and performances are basic for the development of an actively controlled trolley.

Different criteria are involved in the evaluation of current collection quality[1] based on statistical operators of the contact force, duration and count of the losses of electrical contact, static and dynamical displacement measurement of trolley and overhead line. In addition, reliability is a very demanding specification because trolley operates in a very harsh environment (high voltages and currents, high EMI, heavy mechanical fatigue, mechanical impulsive overloads, exposition to variable meteorological conditions and contaminants, etc.).

2.2 Interoperability

The more feasible market for an actively controlled trolley is the future European high-speed railway system. The convergence of the different standards used for overhead line (voltage, frequency, placement) is a long-term solution that involves heavy economic investment and a general agreement between the European railway traffic's operators.

To satisfy this evolving market, an actively controlled pantograph, has to meet very demanding specifications concerning the working run and the overall dimensions:
- To satisfy different height of the overhead line a minimum working run of about 1.5 meters or more is required;
Various standards used for overhead lines need different kind of contact shoes. An actively controlled pantograph may have smaller overall dimensions to place a larger number of trolleys on train roof.

2.3 Aerodynamic Noise

At high speed, the aerodynamic interaction between pantograph and air may be an appreciable source of noise. An actively controlled trolley with a very compact structure should be covered with fairings in order to improve the aerodynamic and acoustic impact [2].

3 Kinematical studies and verifications of dynamical properties

3.1 Preliminary studies

The authors have focused their attention on three different kinematical solutions:

- A traditional structure made of tubular beams and turning pairs (figure 1/a) [2] [3] [4] [5];
- A telescopic structure based on two or more blocks connected by sliding pairs (figure 1/b) [6];
- The overturning pantograph: a curved beam sliding on a circular guide (figure 1/c).

The first proposed solution is the more conservative. Actually there are many passive trolleys optimised for high speed railways, which use similar layout, so there is a diffused know how and a great experience concerning this kind of solution. Authors think that this kind of layout it is not the best solution for a servo-actuated system due to its kinematical and structural complexity that made the application of a servo-actuated system very difficult (figure 1/a).

The second solution (figure 1/b) is very simple and it's the best suited for the design of a servo-actuated system but it has a great drawback concerning the feasibility of long working run required by interoperability specifications.
The overturning pantograph (figure 1/c) is a curved beam that slide along a circular guide made with rolling elements (A,B,C, in figure 2).

![Diagram of Overturning Pantograph](image)

**Figure 2: Kinematical scheme of the overturning pantograph**

The relative angular position between the curved beam and the sliding bow's suspension is also controlled to assure the correct alignment of contact shoes.

### 3.2 Wire actuation system

A simple transmission based on wires and pulleys has been designed in order to obtain a SDOF system and to reduce the number of controlled axis to one. Wire actuation systems are quite often used in robotics and there is a wide literature on this matter [7]. Authors propose to use a wire-based system to protect actuators (DC brush-less motors) from harsh environmental conditions due to high voltages and EMI.

Wire actuation drastically simplifies weight and complexity of the transmission system and solves many troubles concerning local wears due to high cycle repeating motion.

The overturning motion of the curved beam is assured by wires wounded up on a drum. The actuation wires, linked to the curved beam, slide along a low friction guidance system based on rolling elements (figure 3/a).

To assure the correct alignment of the contact shoes the value of relative angle $\theta$, has to change in order to compensate the rotation $\dot{\theta}$ of the curved beam around its ideal axis of overturning (figure 3/a/b):

$$\dot{\theta} = \dot{\theta}_s$$

The angle $\dot{\theta}$ is linked to the rotation of the actuator's shaft ($\dot{\theta}_m$) by the following relation:
where: $R =$ external radius of the curved beam;
$R_m =$ radius of the overturning drum on which is wound up the actuation wire.

Another drum coaxial and integral to the first one move a second wire that is wound up on it.

This second wire, guided by a system of rolling elements and pulleys, is used to control the rotation angle according to the simplified scheme of figure 3.

$$ \dot{\theta} = \dot{\theta}_m \cdot R_m \cdot \frac{R - R_m}{R} = \dot{\theta}_m \cdot \left( R - R_m \right) $$

where $R_a =$ radius of the “alignment drum” on which is wound up the wire used to regulate the value of $\dot{\theta}_s$.

$R_s =$ radius of the pulley linked to the suspension of the sliding bow.

The optimal ratio between $R_a$, $R_s$, and $R_m$ can be found by substituting condition (1) in equation (3): 

$$ R_s = R \cdot \left( \frac{R_a}{R_m} - 1 \right) $$

3.3 Fast CAD-FEM prototyping

Authors have adopted a CAD-FEM procedure to achieve a rough but fast optimisation of the main dimensions and inertial properties of the system according to imposed specifications.

As first step, a 3D parametric CAD model of the pantograph has been designed.
Authors have supposed to build the curved beam as a welded structure with an assigned disposition of constraints and loads. Trolley structure dimension were chosen in reason of imposed specifications as working run, minimum and maximum allowable encumbrance, etc.

The CAD model exported on commercial structural FEM modules has been statically tested with an array of loads and constraints that roughly approximate the worst loading condition which normally affect a trolley on Italian high speed railways [1].

Very conservative criteria such as high stress and safe factor, use of commercial material ad so on, have been adopted to meet specifications concerning low cost and high reliability against mechanical fatigue and overloads. Also wires stiffness and flexibility have been considered in order to evaluate the flexibility of the transmission system.

Parametric dimensions of the model has been modified according to FEM-calculated stress, strain, static and modal deformation.

This procedure has been iteratively applied assuming different curvature radius for the beam and an approximate parametric law concerning the inertial and dynamical properties of the system according imposed specifications.

Dynamical properties of the system have been verified by exporting the 3D model of the trolley, in ADAMS, a multi-body analysis tool.

Authors have focused their attention on the evaluation of the inertial mass of the curved beam reduced to vertical motion $X_p$ of the contact shoes (figure 2).

According to simulation results and imposed specifications, a sub-optimal value of the beam's radius “$R$” has been chosen (figure 4).

Results of numerical simulations also show that system inertial properties may be drastically improved if less demanding specifications concerning maximum and minimum working run are adopted.

In fact, assuming an assigned maximum working run, trolley's reduced mass is a near parabolic function of radius $R$.

![Figure 4: Trolley's reduced mass of the curved beam from working run and its curvature radius R](image-url)
4 Dynamical test and optimisation on a virtual Test Rig

4.1 Virtual Test Rig

Using co-simulation features of Adams and Matlab-Simulink software packages, authors have modelled a virtual test rig in order to verify and optimise system’s dynamical behaviour. The overturning trolley has been tested by imposing a typical motion to the contact shoes. The imposed motion is filtered by a spring, mass, damper system that roughly reproduce the dynamic behaviour of the overhead line (figure 5/a/b). Test rig elements have been accurately validated using experimental data and the virtual model of ATR 90 trolley on which many researcher have previously worked[3]. A wide series of preliminary tests has been carried on with this virtual apparatus to verify the feasibility of the proposed solution.

![Figure 5/a: Test rig simplified scheme](image)

![Figure 5/b: Adams/Matlab/Simulink Co-simulated Test Rig](image)

4.2 Optimisation of sliding bow suspension

Sliding bow characteristic have been tuned using Adams-optimisation tools. Simulation parameters have been chosen to simulate the dynamic behaviour of the collection system at a travel-speed of 200 km/h. The trolley has been tested with a constant lift able to generate a static contact force of about 90N, without any form of feedback control with a aim of design a first hint solution able to work correctly without feedback regulator. This solution should be later refined in order to improve the design of actively controlled system.
4.3 Symmetrical Response Test

Since the trolley's mechanical structure is heavily asymmetric, it is important to verify if travelling direction may influence system performances. Several virtual tests in different conditions (speed, working run, friction of sliding surfaces) has been carried on in order to verify how the dynamical response of the trolley was affected. Preliminary tests, obtained by neglecting the effect of aerodynamic forces, show a quite weak correlation between train travelling direction and system performances (figure 6).

![Figure 6: contact force with different train's travelling directions](image)

4.4 System's Identification

The open loop transfer function $G(s)$ between actuator control torque $T(s)$ and the resulting contact force $F(s)$ in static conditions (train at rest) has been evaluated by using various excitation functions such as sine sweep and pure sine wave applied to the virtual test rig model. Simulation results substantially agree and confirm the presence of a strong system resonance at about 1Hz probably depending on overhead line characteristics (figure 7).

![Figure 7: Magnitude of transfer function $G(s)$ obtained with sine sweep excitation (continuous line) and pure sine (marker points)](image)
4.5 Preliminary tests of an actively controlled system

As preliminary test before the synthesis of a robust regulator, authors have verified the performance of a simple feedback proportional control roughly applied to the virtual test rig.

The test procedure is quite simple: the simulation starts with the pantograph working in passive mode with a known train speed. Once the system reach a steady state, the regulator is activated. At the end of the simulation performance of the regulator is evaluated with various criteria based on statistical operators of the contact force (mean value, variance, etc.).

First simulation results (figure 8/9) show that the system has good performances with low frequencies corresponding to the first mode of the overhead line’s span. For higher frequencies due to droppers there is not an appreciable rejection of disturbance due to the low stiffness of the sliding bow’s suspension that filter the action of the wire actuators.

However simulation shows that the control forces exerted by the wire’s actuator system are quite small (about 100N) so there is no need of gearbox or other kind of transmission system that may reduce system performances.

![Figure 8: Contact force in a virtual test run with a simple proportional regulator](image1)

![Figure 9: Force exerted by actuation’s wire in virtual test run at about 230Km/h with a simple proportional regulator](image2)

5 Conclusions and future hints

The intensive use of CAD, FEM and multi-body analysis tools integrated with numerical software package as Matlab/Simulink has considerably accelerated the
design and the virtual prototyping of an innovative solution of actively controlled pantograph.

The proposed solution, the overturning trolley, has several advantages with respect to other feasible layouts:

1. Low overall dimensions;
2. Low weight and good dynamical response;
3. Long working run with simple and non invasive structure;
4. Small actuator’s size and power required.

The preliminary studies, reported in this paper are very encouraging, so the research activity will continue in order to improve some aspect of the project that are still not deeply investigated.

The design of sliding bow’s suspension and the synthesis of an effective measurement and control system will be the main goal of the future research activities.

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References