An innovative OHL diagnosis procedure based on the pantograph dynamics measurements

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1. Introduction

High speed railways requires intensive investigation on different topics, such as vehicle dynamics, comfort, noise emission, and current collection quality. In particular the performance of the overhead line (OHL) - pantograph system, can be a limiting factor for the maximum train speed, since it affects the power collecting ([1], [2]).

The variation of contact force, exchanged between pantograph and catenary and dependent on pantograph-OHL dynamic interaction, can cause excessive mechanical wear and contact wire uplift (for high values of contact forces), and to high percentage of loss of contact, arcing and electrically related wear if too low values of contact forces occur.

Motivation for dynamic contact force variation are:
- periodically varying stiffness of OHL along the span, related to its structure, (connection of the wires to the masts and the presence of the droppers between contact and messenger wires);
- aerodynamic disturbances due to the turbulent flow incident on the pantograph;
- pantograph and OHL dynamic behaviour;
- irregularity of the contact wire.

Overhead line conditions are very important for power collecting performance: due to this reason an effective maintenance of the OHL is required for an efficient operation of a high speed line. This is also important in view of interoperability, where pantographs optimised for a kind of OHL, are to interact with different kind of catenary.

Since maintenance is related to the knowledge of the OHL condition, several procedures have been developed, to this purpose. Inspections of personnel along the line were used first to find catenary defects and their amount. More recently, railways network management use computerised systems for catenary conditions together with traditional methods [3]: these innovative methods ([4], [5], [6]) are based on specialised vehicles and enable to measure contact wire positioning, stagger, and in some cases also the contact line section reduction. These modern techniques have high security levels for maintenance personnel and avoid traffic interruptions; on the other hand, very sophisticated devices are required.

Aim of the present paper is to propose a technique of overhead diagnostics oriented to the maintenance, able to obtain some information relevant to overhead line conditions using only on board measurements of pantograph dynamics, by means of a set-up applicable on a train for normal service operation. The basic idea is to predict the presence of defect from the effect on the dynamic response of the pantograph. The contact force is the quantity most influenced by the OHL defects, but also the pantograph motion (displacement and velocity) can reveal some of them. Since the set-up for the measurements of the contact force is quite complicated and sensitive to disturbances, it is not conceivable to apply it on an operating train, while the set-up necessary to measure pantograph motion is simpler, and can be mounted on a normal operating train.
In a previous paper [6] a contact force estimation procedure, based on the Extended Kalman Filter has been presented by the authors for the pantograph active control purposes: this approach leads to a great simplification of the measurement set-up with respect to a direct force measurement.

A suitable reference model, able to obtain catenary dynamics information using only pantograph collector head and articulated frame displacement and velocity has been developed and Kalman Filtering estimation procedure has been set-up in order to estimate (instead of directly measure) the contact force.

The estimated contact force enables to obtain some information useful to overhead line diagnostic: variation of contact line vertical positioning, level of wear of the contact wire, droppers failure, suspension set devices failure, contact line tension variation could be detected and examined by means of estimated contact force.

As a first step of the research, in the present work the procedure has been tested numerically: different catenary defects have been modelled and included in a mathematical model of the catenary - pantograph system: several numerical simulation have been performed to generate the input data for the estimation procedure. In order to simulate the dynamic behaviour of the complete catenary - pantograph system, a mathematical model developed at Politecnico di Milano has been used ([7]). Using these results, the scenario corresponding to the considered defects can be compared with the "nominal" catenary status. In the following the modelled catenary defects and their effects on overall system dynamics will be described.

Then some results in terms of system dynamics estimation will be presented: the results obtained from the simulations enable to give a preliminary check of the proposed diagnosis procedure which appears very attractive as a mean to estimate the presence of some of the possible catenary defects and their amount without specific overhead line inspection.

Finally a critical analysis on the applicability of the proposed procedure on real measurements is also carried out, and the necessary improvements and developments are outlined.

2. EKF and the adopted reference model

The proposed diagnostic procedure is based on contact force and catenary motion estimation, using only on-board pantograph displacement and velocity measurements. The procedure adopts the Extended Kalman Filter (EKF) technique and an appropriate reference model (a simplified OHL schematisation and a pantograph), able to estimate the contact force, and to take into account the pantograph-OHL interaction.

The simplified OHL, consisting of three consecutive spans (figure 1), is modelled by means of a tensioned beam, whose characteristics are the sum of the characteristics of the contact wires and the messenger wires of the real catenary. The vertical displacement \( w(\xi, t) \) of the generic catenary point can be written in terms of vibration mode functions \( \Phi_n \) and modal co-ordinates \( q_n \):

\[
w(\xi, t) = \Phi(\xi)^T q(t)
\]

where \( \Phi \) is the vibration mode vector, containing the modal shapes of the tensioned beam with length 3L (being L the length of each span), and \( q \) is the modal co-ordinate vector. The pantograph model is based on a two degrees of freedom system (one for the articulated frame and the other for the collector head): its parameters can be obtained from laboratory frequency response tests. The mass \( m_h \) (representing the collector head) is supposed to be always in contact with the overhead line. Therefore the collector head vertical displacement velocity and acceleration (figure 2) can be expressed as:

\[
x_h = \Phi(V)^T q(t); \quad x_h = V \Phi(V)^T q + \Phi(V)^T q; \quad x_h = V^2 \Phi(V)^T q + 2V \Phi(V)^T q + \Phi(V)^T q
\]

where \( V \) is the train speed, and the prime ‘ denotes the spatial derivatives with respect to the abscissa \( \xi \). Following the Lagrangian approach, i.e. considering: the kinetic energy, the elastic energies (that includes also the contribution of the supporting spring \( k_s \), and the dissipative function, the equations of motion of the overall system (pantograph+OHL) can be written as:
\[ \{ M(t) \ddot{x} + \{ R(t) \dot{x} + \{ K(t) \} x = Q \} \]  

where \( \dot{x} \) is the vector of the independent variables, i.e. the base frame displacement and modal coordinates of the overhead line:

\[
\dot{x} = \begin{bmatrix}
\dot{x}_f \\
q_1 \\
q_2 \\
\vdots \\
q_n
\end{bmatrix}
\]  

The vector \( Q \) represents the lagrangian component of the pre-load applied to the articulated frame of the pantograph.

The matrices in (3) represent the catenary mass damping and stiffness matrices, which are time dependant due to the term \( \dot{z} = V_t \), which represents the pantograph position along the contact wire.

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For the purpose of the EKF use, the contact force \( F_c \) has been included in the extended state vector \( z \) of the reference model:

\[
z = [x_f \; q_1 \; q_2 \; \ldots \; q_n \; \dot{x}_f \; \dot{q}_1 \; \dot{q}_2 \; \ldots \; \dot{q}_n \; F_c]^T
\]  

The reference model equations are:

\[
\dot{z} = \dot{A} + \dot{B} u + \dot{v}
\]  

where \( \dot{u} \) is the vector containing the static force \( P_0 \) applied at the pantograph articulated frame:

\[
\dot{u} = [P_0 \; 0]^T
\]  

\( \dot{A} \) is the system matrix, \( \dot{B} \) is the input matrix and \( \dot{v} \) is modelled as additive white noise to the system.

If only pantograph state variables are supposed available from the measurements set-up, the observation equation is:

\[
\dot{y} = C \cdot z + \dot{u}
\]  

where \( \dot{y} \) is the observed variables vector (collector head and articulated frame displacements and velocities), \( C \) is the observation matrix and \( \dot{u} \) is modelled as additive white noise.

By means of a proper procedure, the pantograph travels only in the central span, switching the state of the system one span back, when pantograph reaches the end of the central span (Figure 2). The two lateral spans therefore are included to reproduce the boundary condition of the central span. In such a way, any desired number of consecutive spans, can be considered, using only few degrees of freedom.
3. Complete modelling of overhead line and pantograph

As previously said, the proposed approach (figure 3) has been up to now tested numerically, generating the measurements to be performed on the real system by means of a computer code able to simulate the dynamic behaviour of the complete catenary - pantograph system (figure 2). The OHL mathematical model for the simulation with the complete system, is based on a finite element schematisation, taking into account the real catenary configuration, the non-linear behaviour of the droppers and the overhead line irregularity. A lumped parameters model has been adopted for the pantograph dynamics. Details on this numerical model can be found in [1].

Different catenary defects have been modelled and included in this mathematical model of the system in such a way to understand their effects on the overall (OHL+pantograph) system dynamics: in particular the considered defects can be divided into two main categories:

- distributed defects such as geometrical variation of contact line due to creep phenomena or/and variation of contact line vertical position related to deviation of droppers length from the nominal value;
- localised defects like broken droppers or registration arm mounting errors.

Some of the above mentioned defects are progressive, other are related to initial mounting errors, or to failure. In the following some results with reference to the “nominal” catenary status (i.e. without any defects) obtained from the simulation will be reported. Then the same quantities modifications due to the presence of each of the considered defect will be reported.

3.1 results with the catenary in nominal status and related estimation
First the results of the simulation with the complete model, and the results of the estimation obtained from the simulated data, are compared. Figure 4 reports the vertical absolute motion of the collector head as a function of position along the line: the typical shape of the trajectory and the effects of the droppers are noticeable. As said above, based on the collector head and the articulated frame motion, both the contact force and the catenary motion have been estimated.

In figure 5 a comparison between central span catenary motion obtained by means of the estimation technique and to detailed FEM model is reported. As can be seen the adopted reference model shows good capabilities for catenary motion estimation too, even if only pantograph motion is available to the estimation procedure. The subsequent figure 6 shows the total contact force. The highest variations occur when the pantograph transits across the suspension s of the OHL.

The spectral component relevant to pantograph span passage frequency (about 1.Hz) and relevant to pantograph droppers passage frequency (about 10-15Hz).

Figure 4. Pantograph front collector head displacement versus train position comparison between simulated and estimated values

Figure 5. Catenary motion: simulation and estimation.

Figure 6. Contact force versus train position: simulated values

Figure 7. Contact force versus train position: estimated values
4. Application to identification of catenary defects

4.1 Overhead line distributed defects
In the following a brief description of the OHL distributed defects considered in the numerical model will be described, and the effects on the current collection will be simulated, testing the capabilities of the proposed procedure to detect the presence of the defect. It must be pointed out that in the estimation procedure, the reference model has always the nominal parameters, the difference in the estimated contact force and catenary motion, between the nominal condition, and the condition with the defect, is due to the input quantities, i.e. pantograph motion, which in the presented cases obtained from simulation with the complete model, in the real condition obtained from the measurements.

4.1.1 Geometrical variation of contact line due to creep phenomena
Catenary wires are tensioned by means of tensioning devices: conductors (and in particular contact wires) experience an increase of their length due to long term viscous creep effects. This produces a geometrical variation of the OHL, as shown in figure 8, more evident if a different level of creep takes place due to a different temperature conditions.
In order to calculate the OHL displacements due to viscous effects, an equivalent traction load which produces the same effects are applied to conductor extremities, and a non linear static analysis is performed, taking into account the non linear effects due to the droppers, because of their non linear mechanical characteristics and to the variation of OHL geometry, also related to he inclined position assumed by the droppers.
Several contact wires and suspension cable lengthening due to long term viscous effects have been considered and contact force estimation has been performed in each case: estimated results were very good in comparison with detailed FEM model ones, not shown here.
In figure 9 the ratio between contact force span passage (1.17Hz) and droppers passage spectral components (10.5Hz) as a function of contact wires and suspension cable lengthening is reported. As can be seen a typical trend of these quantities can be put in evidence the viscous creep effect and using the proposed technique is able to identify this trend.

![Figure 8.OHL geometrical variation due to viscous effects: static calculation from FEM model.](image1)

![Figure 9. Identification: ratio between spectral components of contact force (span passage/droppers passage) for different lengthening of contact wires and messenger wire](image2)
4.1.3 Contact line section reduction due to wear
This effect is reproduced simply reducing the section of the contact wire in the FEM model properties. Uniform reduction of contact wire section has been considered and the estimation of the first frequency of the catenary motion has been evaluated in each case. Figure 10 shows the obtained results in comparison with those obtained by means of detailed FEM model. As can be seen, the identification procedure gives good results, with maximum differences less than 5%. The identified frequency is a parameter that can put in evidence the section reduction due to wear.

![Figure 10](147-figura10-10.jpg)
Variation of first span frequency for contact wire mass variation: comparison between FEM simulation and EKF estimation.

![Figure 11](147-figura11-11.jpg)
Variation of first span frequency for contact wire tension variation: comparison between FEM simulation and EKF estimation.

4.1.4 Effects of friction on tensioning device of the wires
Contact line tension variation may occur when changes of wires length due to temperature are not compensated by the pulleys of the tensioning devices. This fact, that has been reproduced changing wires tension in the OHL FEM model, produces effect both on frequencies of catenary free motion and maximum up-lift of contact wire in coincidence of pantograph passage. By means of the proposed procedure the first frequency of catenary free motion and maximum up-lift of contact wire in coincidence of pantograph passage have been estimated using only pantograph dynamics measurements for several tension changes. As an example figure 12 shows the comparison between estimated uplift of contact wire at suspension in nominal conditions and with a 30% decrease of contact wire tension: change of catenary motion frequency is detected. It can be observed that a tension increase gives the same indication as the mean wear of the contact wire (i.e. both increase catenary free motion frequencies). The two defects could, at least in principle, be distinguished considering also uplift variation of contact wire which is affected only by tension variations. Examining the statistical distribution of the contact force (figures 14 and 15), it can be observed the change of standard deviation and kurtosis, for increased and decreased values of wires tension, with respect to the nominal condition, shown in figure 13.
4.1.4 Error of droppers length

Deviation of droppers length from the nominal value is a systematic cause of geometrical variation of contact line vertical position, which in turn increases contact wire irregularity and contact force dynamic variation. This defect has been introduced by means of an auxiliary FEM model which considers only the contact wire and a stochastic contribution of dropper length. The obtained irregularity is superimposed to the configuration, due to its own weight, that the contact wire assumes between two consecutive droppers.

Since this defect produces an increase of contact wire irregularity, an increase of contact force standard deviation is expected.

The estimation procedure allows to detect this effect as shown in table II, where the estimated value of standard deviation of contact force $\sigma$ and the one obtained from the complete model are reported as a function of maximum tolerance of dropper length.
Nevertheless this symptom cannot be separated from other defects which give analogous effects. Only it can be observed that the shape of statistical distribution is nearer to a gaussian, as indicated by the value of the kurtosis, approaching a value of 3.

4.2 Overhead line localised defects

In the following a brief description of the OHL localised defects considered in the numerical model and their consequences on overall system dynamics will be described.

4.2.1 Dropper failure

The occurrence of broken droppers causes a local variation of contact wire stiffness and as a consequence a variation of pantograph motion and contact force. The inclusion of this effect in the FEM is obtained omitting the considered droppers for what concerns stiffness and damping, and considering it for what concerns the mass: the effect on contact force is shown in fig.16, where the rear collector contact force is show, obtained from the simulation with the complete model. The total estimated contact force, is not able to detect clearly the considered defect, probably due to a limitation of the reference model, which does not take into account the two collectors separately.

Figure 16. Contact force simulated with the complete model on the rear collector: dropper failure

2.3.2 Registration arm mounting errors

A typical defect is the incorrect positioning of the registration arm, which causes a sudden deviation of the contact wire from its natural position. A singularity in the contact force is found, this information indicates some troubles with the registration arm (figure 17)

5. Conclusions

The possibility to correlate OHL defects and contact force has been investigated, and a procedure for the estimation of the contact force, (instead of a direct measurements, has been proposed. Obtained results show that as far as OHL distributed defects are concerned, it is possible to put in evidence correlation between causes and effects: the contact force and catenary motion estimation procedure allows in several cases defect detection using only pantograph dynamics measurements. As far as the concentrated OHL defects are concerned, pantograph motions analysis reveals useful for defect location recognition but not its feature: in particular dropper lacking defect is not
reproduced in the reference model, so it is not possible to detect this problem which, on the other hand, can be revealed by a direct observation of collector and articulated frame relative motion. In any case power collecting performance degradation can be detected by means of the contact force estimation, statistical analysis of contact force may give some help from a diagnostic point of view. Some topics requires further investigations and development:
- improvement of the reference model in order to better recognise also the concentrated defect;
- investigation of the capability of the proposed procedure with respect to measurement noise and disturbances, and in presence of a defect superimposed to a generic irregularity;
- strategy for the diagnosis storage and/or on-board elaboration of the data and their usage for diagnosis.
This last aspect is crucial, because of the great amount of data to be managed.

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