A diagnostic system for overhead lines and pantographs: results from first installation on commuter and high speed commercial trains

Giuseppe Bucca1, Marco Carnevale1, Andrea Collina1, Felice Andreozzi2, Gianfranco Borriello2, Claudio Spalvieri3

1 Dipartimento di Meccanica, Politecnico di Milano, Via La Masa 1, I-20156, Milano, Italy.
2 Contact S.r.l, Via G. Porzio Isola E7, 80143, Napoli, Italy.
3 RFI Rete Ferroviaria Italiana, Piazza della Croce Rossa 1, 00161, Roma, Italy.

*Contact: marco.carnevale@polimi.it

Abstract

This paper presents a diagnostic system for pantograph and overhead line, developed and installed on both high-speed and commuter commercial trains. The system is based on the measurement of collector accelerations and it is aimed at marking an improvement on current scheduled methods for catenary and pantograph maintenance, making condition-based maintenance possible. The set-up proposed is inexpensive and easy to install on commercial service trains. Meaningful indications on pantograph-catenary interaction are obtained by the processing and analysis of collector accelerations; index values are computed in real time during the train run by an electronic board, and compared with alarm limits.

1. Introduction

In the last decades, the need of infrastructure and vehicle constant monitoring has arisen among most of railway companies, especially for high-speed lines. At present days, pantographs and overhead lines are periodically monitored according to a time-based schedule. The monitoring of overhead lines is commonly operated through dedicated inspection vehicles, measuring geometrical parameters such as stagger, contact wire height and thickness, and inspection trains, monitoring pantograph-catenary interaction at commercial speed [1]. The improvement of infrastructure and vehicles monitoring through a diagnostic systems installed on commercial service trains [2] would be a way to provide a constant flow of information, to ease the prevention of failures and service interruption, and to lead towards an event-driven maintenance, with a reduction of the life cycle cost of the vehicle and of the rail infrastructure. It would mark therefore a big improvement in the management of both high-speed and conventional lines.

This paper presents the first results of a diagnostic system for pantograph and overhead equipment condition monitoring, developed and installed on both high-speed and commuter commercial trains. It is a rolling stock-based system, now installed on the entire fleet of the new Italian high-speed train ETR1000, and as a prototype on one electrical locomotive e464 adopted for commuter train service (160 km/h) [3]. The main idea behind the proposed diagnostic system is the use of pan-head accelerations to identify the quality of the pantograph-catenary contact, to develop a non-intrusive and maintenance free system able to recognize relevant defects. A low number of sensors is exploited to contain costs of the instrumented pantograph and to make it feasibly installable on an ordinary fleet of trains. Suitable data processing techniques allow calculating in real time relevant indices to be compared against a reference condition, depending on operational parameters such as train speed or
pantograph preload. The analysis of these indices permit the diagnosis of the possible cause of the fault, while the trend of the index would indicate the rate of deterioration of the found defects. Different algorithms allow the detection of overhead-line local defects (e.g. misregulation in suspension, mid-point anchors, span overlaps), distributed defects (e.g. irregularity in contact wire height), and pantograph failures (e.g. incorrect contact force, collector force unbalance, anomalous behaviour of pan-head suspension).

2. Sensor layout

The accelerometers installed on the pantograph are based on fibre optic technology, which allows, due to its intrinsic insulating properties, to connect the sensors to the acquisition and processing unit placed in the car-body, without any need to power them. The system is made of two mono-axial accelerometers, measuring vertical acceleration. This solution is cheaper than the standard set-up used for the measurement of contact force, which requires a higher number of sensors. It is also easier to set, since the ability of optical fibres to insulate electrically the sensor from the conditioning and data-acquisition unit permits very straightforward wiring. Moreover, the use of accelerometers allows extending the measurement to a frequency band larger than the 0-20 Hz commonly used in contact force measurement. The bandwidth of the system is 0.5-300 Hz, which allows gathering information about the excitation of collector flexural modes, these modes being a detector of the presence of defects in the overhead line [4].

One accelerometer is mounted on each contact strip, placed in a crossed configuration (front-right and rear-left), so as to record differences in right-side and left-side motion generated by lateral displacement of the contact force due to stagger. Figure 1 shows an example of the sensors installed on the asymmetrical high-speed pantograph WBL (Figure 1a), (ETR1000 train), and the wiring on the symmetrical low speed pantograph FS52-92 (Figure 1b), (e464 locomotive). Particular care was taken to guarantee a minimum curve radius of the optical fibre greater than 50 mm, and to avoid optical fibre flexural movements during operation. In addition, the sensor’s position was chosen so as not to interfere with periodical strip substitution operations.

![Figure 1](image)

**Figure 1:** (a) Detail of the optical sensor on the high-speed WBL pantograph. (b) Optical fibre wiring on the low speed FS52-92 pantograph.

3. Data processing and geo-localization system

The essence of the diagnostic system is the comparison of significant measured quantities against a reference condition, depending on operational parameters such as train speed or pantograph preload.
Acceleration data are real-time processed during train run by suitable algorithms, which elaborates the raw data in order to get summary indexes representative of the status of the overhead line and of the pantograph itself. These indices are compared with alarm limits as to detect the turnout of a defect. An alarm can then be transmitted, with its proper level of priority, both to the train data network (to be implemented) and to the ground via GPRS connection. The on-board processing of raw signals allows reducing the amount of data, so that only diagnostic indicators are transmitted via GPRS. The storage in a wayside server of all the elaborated data, allows creating a database and a long-term monitoring of pantographs and infrastructure. Two levels of analysis are therefore performed: on board analysis, aimed at the real time identification of local and distributed catenary defects and pantograph fault. Remote analysis, consisting in the long-term comparison of the data acquired, as to define a trend for the infrastructure and the pantograph status. The latter is currently at its first stage, in which a data-base is being built.

The algorithms are based on the evaluation of the Root Mean Square (RMS) of accelerations, in order to highlight the increase of power in the signals arising due to the presence of a defect [4]. Different defects can be identified by adopting windows of different length. A short time window (e.g. 0.2 s) with a high overlap can identify local defects in the infrastructure. These defects increase the power content of collector acceleration generating an impact and exciting pantograph modes of vibrations, especially flexural modes of the collectors. A long time window, corresponding to about 1 km and without overlap, allow to detect at the same time an alteration in pantograph mechanical behaviour as well as contact line distributed defect. Distributed defects, such as contact wire height, increase the level of accelerations in correspondence of the defective line section. Pantograph malfunctioning can modify the dynamic interaction of the pantograph-catenary couple, changing therefore the RMS level during the train run. The diagnostic system being installed on the entire fleet, the off-line analysis allow to discern if an increase of RMS value should be ascribed to pantograph fault or catenary defect: a repetition of the threshold exciding occurring at the same location for several trains show a problem with the infrastructure. A repeated threshold exceeding on the same train indicates an alert with pantograph to be transmitted to the train data network.

Diagnostic indicators for the status of the components are generated together with train speed, and train position, which needs to be as accurate as possible in order to identify the real position of the detected defect, as to ease the infrastructure management, and to create a data-base in which the long-term behaviour of the infrastructure can be monitored. Speed, line type, GPS position, operating pantograph and master loco are retrieved from the vehicle logic through the bridge MVB/Ethernet and feed to the electronic board running the diagnostic algorithms.

For the time being, the train positioning system is based on GPS data. A more accurate geo-localization system is under development, relating the GPS path of the line to the corresponding rail milestone. It is based on GPS data, odometer data and digital map database. By means of map-matching technique, the acquired GPS position is projected on the line database, as to identify the vehicle location on that track segment. A robust fitting method is then used to calibrate the detected odometry to get accurate train positioning. The algorithm can run in real time during the train operation to correlate the actual position to each index calculated by the diagnostic system.

4. Installation on ETR1000 high-speed train

The data presented in this paper have been gathered in the first months of commercial service of the new high-speed train ETR1000, and refer therefore to the entire Italian high-speed line. In particular, this starting period is being used to set a database of RMS values along the entire line, in order to set reference thresholds corresponding to the actual status of the line. Reference thresholds will be defined for both overhead line and pantograph diagnostic.

Figure 2 and Figure 3 show an example of the RMS for respectively 25 kV and 3 kV pantographs. RMS values with long-time window are computed for four frequency bands, each of them representing a
particular range distinctive of pantograph-catenary dynamic interaction (as explained in the following). In the figures, the intervals pinpointed by dashed lines highlight the instants in which the diagnostic pantograph is raised and in operation. For given operational parameters (pantograph orientation and speed) RMS values show a slight variability, underlined in the distributions of the bar diagram of Figure 2b and Figure 3b, due to slight variation of the dynamic interaction of the pantograph with each catenary section.

In the case of infrastructure diagnostics, the up-to-date RMS values will be compared to reference values associated at every milestone position along the line (km), in order to analyse the long-term behaviour of each part of the line.

Figure 2: long time window RMS – 25 kV pantograph. Speed 300 km/h. (b) RMS distribution.

On the other hand, when interested in pantograph diagnostic, the results for a pantograph-catenary couple are repetitive enough to set a unique threshold value valid in all Italian high-speed lines. The threshold values can be defined on the base of the average value of the RMS distributions and its standard deviation (Figure 2b and Figure 3b).

Table 1 compares the frequency bands for 25 kV and 3 kV pantograph.
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<thead>
<tr>
<th>25 kV pantograph</th>
<th>3 kV pantograph</th>
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<tbody>
<tr>
<td>1) Frequency range 0.5-5 Hz</td>
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<tr>
<td>2) Frequency range 5-30 Hz</td>
<td>2) Frequency range 5-30 Hz</td>
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<tr>
<td>3) Frequency range 150-185 Hz</td>
<td>3) Frequency range 115-145 Hz</td>
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<tr>
<td>4) Frequency range 0.5-180 Hz</td>
<td>4) Frequency range 0.5-180 Hz</td>
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Table 1: Frequency ranges for RMS evaluation adopted in pantograph diagnostics.

The only frequency range differing is number three.

- Band number one is related to pantograph behaviour at span-passing frequency, the corresponding RMS value being therefore an indicator of all the components affecting low frequency, such as the air spring and damper at the base of the frame for pantograph, contact wire tension for catenary.
- Band number 2 includes the frequency range related to dropper passing frequency, and is therefore affected by an anomalous behaviour of the pan-head suspension for pantograph, dropper behaviour for catenary. Laboratory tests proved that a damage in pan-head suspension generates anomalous values in the RMS corresponding to band 2, leaving RMS of band 1 unchanged.
- Band number 3 is a very narrow band including the natural frequency of one flexural mode of the collectors. An alteration of this frequency due to a damage of the collector would change the level of acceleration in this band, and would therefore be detected by the RMS analysis.
- Band number 4, mainly aimed at identifying contact wire irregularity, can be also used to evaluate, together with band number one, the correct value of the uplift force exerted by the air spring pressure.

5. Installation on e464 electric locomotive for commuter trains

Data acquisition from the conventional low speed pantograph FS52-92 is relevant in the present work since it allows investigating the behaviour of the diagnostic system on a pantograph-catenary couple very different from the high-speed one investigated in paragraph 4, both from the point of view of mechanical characteristic and operational speed. During a 6-month testing period, it was possible to monitor most of the 3 kV conventional overhead lines of a wide area in the North-West of Italy. Results were gathered across about 180,000 km of service, the instrumented pantograph being installed on a commercial service locomotive. Several data acquisitions on the same lines and at the same speed allow verifying the repeatability of the proposed method, which is essential for developing a reliable condition-based maintenance system.

In this paper, results referring to the analysis for identification of local defect of the overhead line are presented. The root mean square value (RMS) of both accelerations is calculated over a mobile window of short length (e.g. 0.2 s) and a high level of overlap (e.g. 90%), in order to highlight the power increase of collector accelerations at the location of local defects. The data obtained with different train runs are then compared to verify the persistence of the main RMS peaks at the same positions, which indicates the presence of a relevant infrastructure defect.

Figure 4 shows an example of the results obtained by RMS analysis, corresponding to the accelerometers placed to the leading (a) and trailing (b) contact strips. All the repetitions along a 150 km line are reported. The maximum commercial speed is 160 km/h, and some train stops can be identified in the figure where the RMS value gets to zero. The analysis showed that in the case of FS52-92 the repeatability of RMS peaks is higher when only the 0.5-50 Hz is considered. This marks a difference with the results obtained in [5], in which this algorithm gives the best results for a wider frequency range.
also including the natural frequencies of flexural modes of the collector, due to deformability of the support holding the sensors to the collector of FS52-92 pantograph.

By looking at the RMS of Figure 4, corresponding to the 0.5-50 Hz frequency range, five remarkable peaks are detected, highlighted in the figure by a red square. The experimental data available are processed in the off-line analysis in the following way: only RMS peaks occurring at most of train passages are considered, disregarding as low priority points the cases corresponding to a low number of occurrences.

![Figure 4: RMS values of pan-head accelerations. (a) Leading strip. (b) Trailing strip.](image)

It is possible to observe that most of peaks are only visible in one signal, on leading or on trailing contact strips, confirming the necessity of two sensors. After verifying the repeatability of the system in detecting an RMS peak at the same location, the final step of the work will be an evaluation of a threshold to identify which peaks are remarkable, and which is the level of priority for maintenance. This can be done by a field analysis aimed at identifying the correspondence between the detected RMS peaks and the status of the overhead line, mainly from a mechanical point of view. Thanks to the cooperation with Rete Ferroviaria Italiana, this analysis is being performed by correlating the results from the diagnostic system to those available from inspection vehicles.

6. Conclusions

A diagnostic system based on pantograph accelerations, using only two sensors placed on pan-head collectors, was installed on commercial high-speed and commuter trains. The paper presents the results obtained during the first months of commercial service, demonstrating the proper working of the electronic board running the diagnostic algorithms. The board retrieves information such as speed, line type, GPS position, operating pantograph and master loco from the vehicle logic. This operational information are integrated with the results of two diagnostic algorithms, computing RMS of pan-head acceleration over mobile windows of different lengths, in order to identify catenary local and distributed defects as well as pantograph defects.

The aim of the proposed system is providing a diagnosis of pantograph and overhead line status, marking an improvement on current scheduled methods for catenary and pantograph maintenance, and paving the way to condition-based maintenance. The first step of the work, consisting in the creation of a data-base as a reference of the status of line and pantographs is now concluded. The following step will be the long-term trend analysis and the evaluation of different thresholds to identify which peaks are remarkable, and which is the level of priority for maintenance.
7. References


