Condition monitoring of the rolling stock and infrastructure: results of a pilot project

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Abstract

The application of Prognostics and Health Monitoring (PHM) concepts in rail vehicles and railway infrastructure is a rapidly growing field of research, and extensive efforts are being spent with the aim of improving the reliability and availability of railway systems and of substantially reducing maintenance costs by switching from time-based to event-driven maintenance policies. This paper presents the results of a research project in which concepts were developed and demonstrated for the health monitoring of the rolling stock (traction equipment) and of the railway infrastructure (track and overhead equipment). A prototype monitoring system was installed on a E464 locomotive and results were gathered across a time span of 14 months from December 2014 to January 2016.

1. Introduction

The application of Prognostics and Health Monitoring (PHM) concepts in rail vehicles and railway infrastructure is a rapidly growing field of research [1]-[5], and extensive efforts are being spent with the aim of improving the reliability and availability of railway systems and of substantially reducing maintenance costs by switching from time-based to event-driven maintenance policies.

This paper presents the results of a research project in which concepts were developed and demonstrated for the health monitoring of the rolling stock and of the railway infrastructure (track and overhead equipment). A prototype monitoring system [6] was installed on a E464 locomotive and results were gathered across a a time span of 14 months from December 2014 to January 2016.

The monitoring system includes three modules, which are aimed at the condition monitoring of the traction system, of track state and of the pantograph-catenary couple respectively. More details on the three units are provided in Section 2 of this paper. The monitoring system was interfaced with the MVB of the loco: in this way, some relevant parameters describing the working condition of the loco such as speed, direction of movement, odometry, traction/braking/coasting mode can be used in the monitoring and fault diagnosis process. The system is also provided with a GPS-based geo-referentiation system so that the measured data can be examined in terms of their trend not only with time (or with the mileage run) but also with the position of the vehicle on the track.

The processing of measures is performed by two CPUs installed on the loco and synthetic packages of diagnostic indicators are generated and sent to a wayside server through GPS wireless data transmittion. These data are stored on the wayside server and used to generate a historical data-base of the condition of the vehicle’s monitored components (bearings in the traction system, pantograph), as well as a real-time map of the infrastructure condition (track and overhead equipment).

2. Architecture of the monitoring system

The monitoring system consists of three modules having different aims:

- the condition-based monitoring of the bearings belonging to the motors and gearboxes and those installed on the axleboxes;
- the monitoring of track state from vehicle dynamics measurements performed on the train, to drive line maintenance actions based on the objective measure of train-track interaction:
- the condition-based monitoring of the pantograph-catenary couple.

Data acquisition and processing is automatically performed by an on-board diagnostic unit and the diagnostic indicators are sent via GSM to a wayside unit where they are stored and used for trending analysis. In the following of this section, the three CBM units are presented. Then, a description is provided of the hardware for data acquisition and processing.

2.1. The traction monitoring unit

For the monitoring of the traction system, accelerometers and dual sensors (acceleration + temperature) are used. All four motors and gearboxes and all eight axle boxes are monitored. Figure 1 shows the bearing positions on the motor, gearbox and axle bearing.

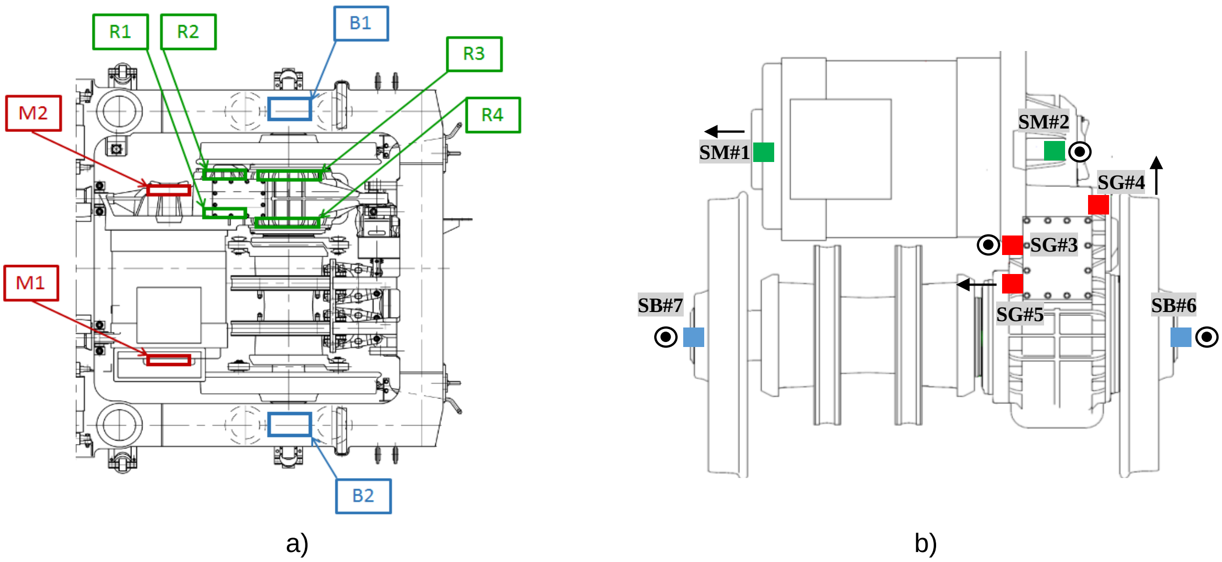

Figure 1. a) bearings of the traction monitoring unit. b) position of the sensors

The vibrations of the bearings are measured by IEPE industrial accelerometers placed close to each bearing. A tachometer sensor is installed in correspondence of each motor and detects the number of revolutions. The accelerometers installed on the gearbox-motor assembly are PCB IMI-Sensors T0602D01 and PCB IMI-Sensors T0603C01 with sensitivity of 100mV/g and range up to 50g. On the bushings, Measurement Specialties 8021-01-0500 accelerometers with range up to 500g are installed, due to the higher level of acceleration expected on the axle. All the used sensors are dual-sensors measuring acceleration and temperature

The track state monitoring unit

The condition of the track is monitored by measuring the vertical and lateral acceleration of the vehicle at the axle-boxes, bogie frame and carbody. The track state monitoring unit includes therefore two bi-axial MEMS accelerometers measuring the vertical and lateral acceleration of the two axle boxes of the same axle, three mono-axial accelerometers measuring the vertical acceleration of the bogie frame at three distinct points, and two mono-axial MEMS accelerometers measuring the vertical and lateral acceleration of the car body above the centre of the trailing bogie. The acceleration signals are low-pass filtered with a cut-off frequency of 50 Hz and sampled at 1650 Hz.

2.2. The pantograph-catenary monitoring unit

The condition of the overhead line is monitored by measuring the vertical acceleration of the pantograph collector. The sensors are based on fiber optic technology, which allows, due to its intrinsic insulating properties, to connect directly the accelerometers to the acquisition and processing unit placed in the car-body, without any need to power the sensors. This is quite important for a system thought for application on commercial trains, since it reduces the costs of installation and equipment. One optical accelerometer is mounted below each contact strip, placed in a crossed configuration on the pan head collector (front-right and rear-left), so as to record differences in right-side and left-side motion generated by the lateral displacement of the contact point between the pantograph head and the catenary due to the stagger. The bandwidth of the system is 0.5-300 Hz.

2.3. The data acquisition and processing hardware

All signals are acquired by two data acquisition systems, one per bogie. The sampled data are sent for processing to a central system (industrial PC) that manages the entire apparatus. The data acquisition system for the leading bogie is positioned under the car-body and the one for the trailing bogie is located in the car-body. The connection between the PC and the on-board system is via Ethernet cable, while the connection to the leading bogie's acquisition system is performed by means of wireless transmission. In order to ensure redundancy in the communication between the leading bogie data acquisition system and the central unit, a physical connection via Ethernet cable is also implemented. The complete layout of the data acquisition and processing system is shown in Figure 2.

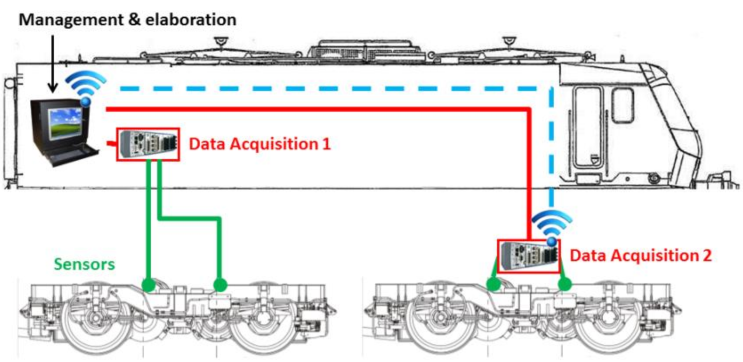

Figure 2: Schematics of the data acquisition and processing hardware.

Data acquisition is performed by two National Instruments CompactRIO devices. These are reconfigurable systems equipped with an FPGA module for real-time programming. The industrial PC is a MOXA-V2416 installed in a rack placed on board the car-body in the rear cargo area of the locomotive. The PC is connected to a GPRS module which allows the transfer of the diagnostic packages to a wayside server.

3. Exemplary results of fault diagnosis for the traction equipment

Vibration data for rolling element bearings have been acquired at high sampling frequency, namely 25600 Hz and collected in different operating conditions: train speed and direction, motor torque temperature. In particular, some rules have been defined in order to acquire data only in suitable operating conditions, mainly in constant speed, and with an average interval of about 5 minutes between two consecutive acquisitions. In the monitoring period, a total amount of about 25000 acquisitions have been collected. Data acquisitions have been classified depending on the operating condition. For each class the bearing health has been evaluated as function of the train mileage by means of suitable damage indicator. Fault identification has been performed mainly by means of envelope tools [7] due to the nature of the vibration signal for a damaged bearing. In particular peaks in correspondence of the bearing defect frequencies have been extracted from the envelope spectrum. BPFO, BPFI, FTF and BSF bearing defect frequencies, corresponding to a defect on outer race, inner race, cage and roller respectively, have been investigated. The final fault indicator δ is then evaluated as the ratio between the number of acquisitions in which peaks in the envelope spectrum exceed a statistical threshold [8] and the total number of samples falling in a moving time window. The upper limit of the fault index is equal to one and indicates that in all acquisitions a bearing damage is clearly detectable, that is a probability of a defect is very high.

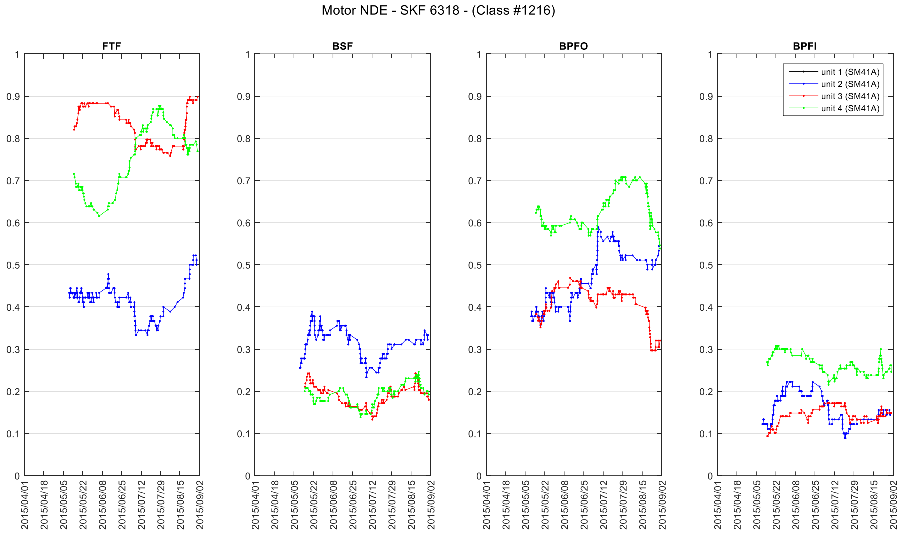

Figure 3. Trends of the damage indicators for the ball bearing in the NDE side of the motor.

The procedure has been repeated for all bearings of all four traction units. The trends of these indicators are shown in figure 3 for the ball bearing in the Non Driving End (NDE) side of the motor. It is possible to highlight high values of the indicator for a possible damage on the cage (FTF) and outer race (BPFO). The inspection of the bearing performed after the monitoring period has actually revealed the presence of cage and outer race defects on these bearings.

4. Exemplary results of the track condition monitoring

A methodology for the condition monitoring of track state was developed based on the use of acceleration signals acquired during train service. A useful representation, in order to highlight the strong correlation between acceleration measurements and track condition, is obtained applying a Specgram technique to the signals. This 3-D graph (shown in Figure 4) reports on the horizontal axis the position along the line of the vehicle and on vertical axis the wavelength content of the signal, while the color map defines the amplitude of the R.M.S. of the acceleration signal. This representation points out clearly possible track defects, providing information on their location and wavelength, thereby providing an overall evaluation of the line condition. It can be concluded that the study of the track geometry seen from vehicle's dynamics point of view is of fundamental importance for the evaluation of the line condition and for the definition of track condition monitoring approaches: as a matter of fact traditional measurement methodologies (for instance 3 points based measurements) are able to identify only irregularity profile with wavelengths under 30 whereas the experimental set up adopted here can go beyond this limitation allowing the identification of higher wavelength irregularity, besides enabling the continuous monitoring of the track with a relatively low effort spent.

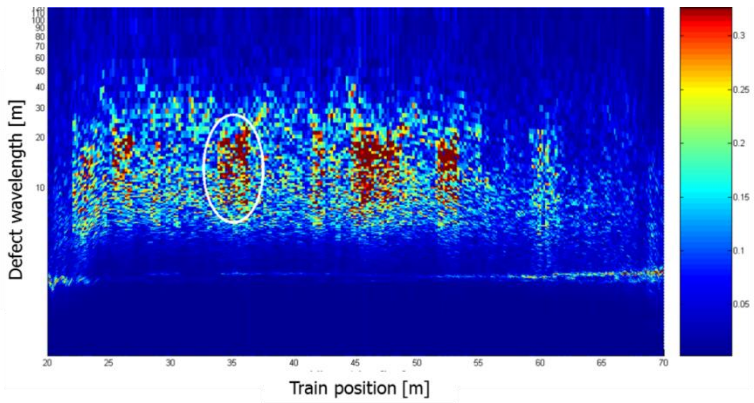

Figure 4: Example of Specgram of bogie lateral acceleration

Owing to the confirmed correlation between track condition and train dynamic response, a step forward was done focusing the attention on the correlation between the frequency content in the acceleration signals and the track defect wavelength. Figure 5 shows an example of the results obtained. A track section on the conventional line Torino Porta Nuova – Genova Brignole is taken as a reference and the vertical bogie acceleration is analysed in different time periods covering seven months of service. In the first subplot the vehicle speed is reported as a function of train position for different vehicle runs. The second subplot shows the vertical acceleration signal pass-band filtered in the 3-40Hz frequency range. The third subplot reports the power spectral density (PSD) of the vertical bogie acceleration and finally the lower subplot shows the r.m.s. of the same signal computed over a 250m moving window.

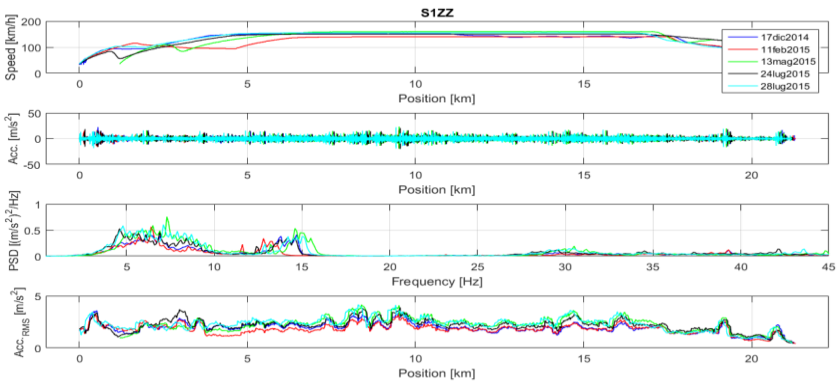

Figure 5: Monitoring of track state for the Torino – Genova line from December 2014 to July 2015

From the vehicle speed diagram it can be observed that the speed profiles are subject to some variability which is reflected in a variation of the moving average r.m.s. recorded in different runs. Hence, it is important that the condition based monitoring methodology properly takes into account the effect of speed in order to distinguish between an evolution of the defect and the effect of speed variations. Moreover, from the trend of the moving window r.m.s. it is possible to identify track segments producing higher levels of vehicle vibration, which can be interpreted as produced by higher levels of track irregularity or other track defects. The evolution with time of these track segments can be monitored by proper interrogation of the track data-base being built based on the measurements collected.

5. Exemplary results of the monitoring of the pantograph-catenary couple

During the 6-month testing period, it has been possible to monitor all the 3 kV conventional overhead lines over a wide geographical area in North-West Italy. Several data acquisitions were performed on the same lines and at comparable speed, allowing to verify the repeatability of the diagnostic information obtained, which is essential for developing a reliable condition-based maintenance system. The analysis performed is aimed at identifying local defects of the overhead line, i.e. singular points which can affect the stability of current collection. These defects can be either the result of construction imperfections or infrastructure degradation. The root mean square value (RMS) of both accelerations is computed over a mobile window of short length (e.g. 0.2 s) with a high level of overlap (e.g. 90%), in order to highlight the power increase of collector accelerations at the location of local defects [9]. The main idea behind this technique is to identify the power associated with the acceleration peaks, so as to distinguish occasional peaks from those generated by a real defect. 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. The use of accelerometers allows extending the measurement to the frequency band 0.5-250 Hz, which is larger than the 0-20 Hz usually allowed by contact force measurement. This enables the acquisition of useful information on the level of excitation of collector flexural modes, which are usually excited by contact line singularities. However, the analysis showed that the identification of RMS peaks with respect to the background level is easier when only the range 0.5-50 Hz is considered. This is due to the flexibility of the support holding the sensors in the pantograph adopted in the present work, and marks a difference with respect to the results obtained in [9].

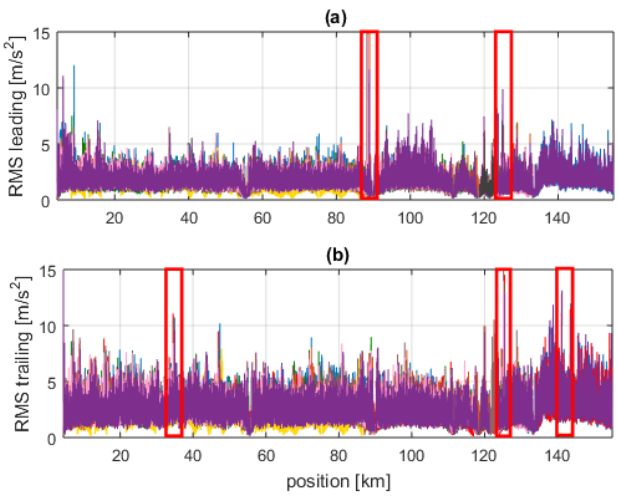

Figure 6: RMS values of pan-head accelerations. (a) Leading strip. (b) Trailing strip.

Figure 6 shows an example of the results obtained by RMS analysis, corresponding to the accelerometers placed to the leading (a) and trailing (b) contact strips (Frequency content 0.5-50 Hz). 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. Five remarkable peaks are detected, highlighted in the figure by a red square. The identification of hot-spots is made by disregarding the peaks that are not confirmed in several repetitions, such as the ones at km 6 and km 9 for the leading strip. It is possible to observe that most of peaks are only visible in one signal, confirming the necessity of two sensors. 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 means of a field analysis aimed at identifying the correspondence between the detected defect and the status of the overhead line.

6. Conclusions

In this paper, a monitoring unit was presented which is capable of providing detailed information on the condition of the roller bearings in the traction unit as well as of the state of the railway track and of the pantograph-catenary couple.

The unit was installed on a E464 locomotive and is now successfully operating since December 2014. Data are being continuously measured and treated according to a number of fault diagnosis technologies, whose indications are compared with return from vehicle maintenance and from the field. A vast measurement data-base is already available and is being continuously expanded, allowing the assessment and validation of the fault detection algorithms being developed as well as a a real-time map of the infrastructure condition.

A next part of the research will be to establish direct links between the condition monitoring data-base and the maintenance of the vehicle and of the track, so that the detailed diagnostic information availale can be directly fed in the maintenance decision process.

Acknowledgements

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