CHEMICAL ENGINEERING TRANSACTIONS

VOL. 33, 2013

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

Guest Editors: Enrico Zio, Piero Baraldi

ISBN 978-88-95608-24-2; **ISSN** 1974-9791

DOI: 10.3303/CET1333124

Experimental Evidences in Bearing Diagnostics for Traction System of High Speed Trains

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Rolling element bearings are the most critical components in the traction system of high speed trains. Monitoring their integrity is a fundamental operation in order to avoid catastrophic failures and to implement effective condition based maintenance strategies. Generally, diagnostics of rolling element bearings is usually performed by analyzing vibration signals measured by accelerometers placed in the proximity of the bearing under investigation. Several papers have been published on this subject in the last two decades, mainly devoted to the development and assessment of signal processing techniques for diagnostics. The experimental validation of such techniques has been traditionally performed by means of laboratory tests on artificially damaged bearings, while their actual effectiveness in specific industrial applications, particularly in rail industry, remains scarcely investigated. This paper is aimed at filling this knowledge gap, by addressing the diagnostics of bearings taken from the service after a long term operation on the traction system of a high speed train. Moreover, in order to test the effectiveness of the diagnostic procedures in the environmental conditions peculiar to the rail application, a specific test-rig has been built, consisting of a complete full-scale train traction system, able to reproduce the effects of wheel-track interaction and bogie-wheelset dynamics. The results of the experimental campaign show that suitable signal processing techniques are able to diagnose bearing failures even in this harsh and noisy application. Moreover, the most suitable location of the sensors on the traction system is proposed, in order to limit their number.

1. Introduction

The mechanical components of a traction system of high speed trains (HST) have to operate reliably on various operating conditions and tracks. A statistical approach to forecast the residual life of these components and plan maintenance schedules is the less economically appealing the higher is the number of the components whose integrity is crucial for the functioning of the train. In HSTs with a distributed traction system, the complexity of the system results in frequent maintenance operations with high risk of unexpected stopping failures. Under these circumstances, more sophisticated maintenance strategies, such as condition based maintenance (CBM), represent an efficient alternative to the traditional approach. CBM is based on the monitoring, during operation, of some system parameters, which allow the definition of system health state. Rolling element bearings (REBs) are the components most prone to failure in the traction system of HST are bearings.
REBs are often subjected to heavy operating conditions and to aggressive environments, especially in rail applications (Fec and Moyar, 1987). Bearing operating conditions can be characterized by contact fatigue, internal clearance, corrosion and bad lubrication, including the use of degraded lubricant and either insufficient or excessive quantity of lubricant. Moreover, defects on bearings components can also originate during the assembly phase, owing to an incorrect preload or misalignment and shaft deflection. Regarding environmental conditions, the presence of dust, dirt or aggressive media like water, as well as current discharges and external heating can produce damages which lead to wear and premature fatigue failure of bearings.

Please cite this article as: Pennacchi P., Chatterton S., Vania A., Ricci R., Borghesani P., 2013, Experimental evidences in bearing diagnostics for traction system of high speed trains, Chemical Engineering Transactions, 33, 739-744 DOI: 10.3303/CET1333124

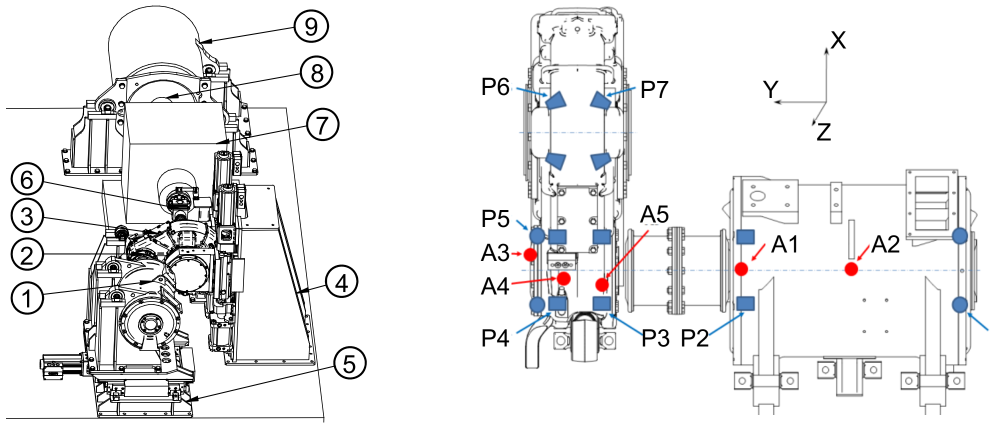
In literature, most of the papers devoted to bearing diagnostics, are focused on signal processing techniques applied to vibrations measurements. Many different techniques have been developed for the detection of bearing damages: from envelope analysis up to recent developments of squared envelope spectrum (Randall, 2011), 2nd order cyclostationary analysis (Capdessus et al., 2000), spectral kurtosis (Antoni and Randall, 2009), empirical mode decomposition (Yu et al., 2005) and minimum entropy deconvolution (Pennacchi et al., 2011). Whereas strong attention has been paid to the development of techniques and algorithms, which were able to identify malfunctioning in bearings, less importance has been devoted to the investigation of the bearing behavior in real railway applications. One of the few papers focusing on real damaged bearings taken from the service is Ferreira 2003, in which data related to about 47,000 failed bearings, installed on wheel axles of freight cars, were collected and classified, depending on the operation time, to determine the failure distribution. The relevant number of considered bearings allows observing that the most frequent defects are caused by contact fatigue, which creates micro-cracks under the surfaces of the bearing parts. These micro-cracks propagate with the functioning cycles and finally reach the surface creating a spall. Failures usually occur in the outer ring, in the inner ring and in the rolling elements. Considering all the bearings taken from the service, independently from their installation date, the most recurrent failure is represented by fatigue in the outer ring (58 %). Although fatigue in inner ring is the second failure mode in order of appearance, it affects only 13 % of the damaged bearings. Only 5 %, 4 % and 3 % of railway bearings are affected by oxidation, micro-fatigue and fatigue on rolling elements respectively. Other damages are merged in one category, which represents the remaining 17 % of the amount.

Since the availability of real field data is limited, test-rigs are often used to reproduce the bearing operating conditions. Test-rigs aimed at studying bearing wear in general applications were presented in various papers (Sawalhi and Randall, 2008). Laboratory facilities are generally characterized by low or medium installed power with testing conditions not as severe as the operating ones and very limited environmental noise. Moreover, no test-rigs are specifically devoted to train applications.

In this paper, a wide experimental campaign, performed to develop a suitable CBM approach for the bearings of the traction system of HST, is presented. The experimental activity was performed on a test-rig designed and built-up on purpose. The test-rig was realized by using components (i.e. traction motor and gearbox) taken from a HST and equipped with devices able to reproduce actual train operating conditions and wheel-track interaction. During the experimental campaign, brand new and worn bearings, taken from the service of a HST traction system, were tested. The configuration with brand new bearings has been assumed as reference condition.Vibration signals, measured by means of accelerometers placed on the casings of gearbox and motor, were processed with different signal processing techniques (envelope analysis, 2nd order cyclostationary analysis, spectral kurtosis and empirical mode decomposition) in order to identify the most suitable one for bearing diagnostics. In the paper, the results obtained by the application of the spectral kurtosis (SK) will be discussed. The results obtained by this signal processing technique were also useful for the definition of the number and the position of the sensors composing the on-board diagnostic system of the bearings of future HST traction systems.

2. Description of the test-rig

As already stated, test-rigs usually employed for the diagnostics of bearings were traditionally characterized by low installed power. Since the diagnostics effectiveness depends also on the actual operating conditions of the train in terms of speed, motor torque, effect of the wheel-track interaction and environmental noise, the test-rig shown in Figure 1(a) has been designed on purpose to take into account all these aspects. In particular, a complete HST traction system has been considered: a 265 kW 4-poles asynchronous HST motor is connected to the input shaft of the HST gearbox by means of a toothed coupling. The braking torque is providede by a braking system composed of a braking motor and an industrial gearbox connected to the HST traction system through a double cardan shaft. In particular, the braking motor is speed-controlled, whereas the traction motor is torque-controlled. In order to consider the real operating conditions of the train, the traction system was mounted on two moving platforms. The traction motor is moved in the horizontal plane allowing the effect of different alignments of the toothed coupling to be considered. The second platform supports the output shaft of the gearbox and shakes it in the vertical direction. These platforms allow reproducing the relative movements, caused by the wheel-track interaction, of the motor suspended on the bogie primary suspension and the gearbox connected to the wheel axle. The movement of the platforms, the rotational speed of the traction motor, the management of test sessions and the related tasks were performed by a Supervision System (SUSY). SUSY is composed of a PC connected to a National Instruments PXI chassis with real-time (RT) embedded processor that warms-up the test-rig, performs the system checkup, starts up and manages the tests.



(a) (b)

Figure 1: (a) Test-rig layout. ① HST motor, ② HST toothed coupling, ③ HST gearbox, ④ Vertical moving platform, ⑤ Horizontal moving platform, ⑥ Double cardan shaft, ⑦ Additional industrial gearbox, ⑧ Double cardan shaft, ⑨ Braking motor; (b) Traction system arrangement with bearing position (from P1 to P7) and accelerometer position (from A1 to A5)

Figure 1(b) shows the HST traction system along with the number, the position and the type of installed bearings. The motor shaft is supported by two REBs: the non driven end (NDE) side of the shaft is supported by a single row ball bearing, whereas that placed at the driven end (DE) side (P2) is a single row cylindrical roller bearing. Both bearings are lubricated with grease. The two helical gears of the gearbox are supported by 5 oil-lubricated bearings. Two cylindrical roller bearings (P3 and P4) support the input shaft, while an additional four-points ball bearing (P5) bears the axial force caused by the helical gears. The wheel axle is supported by two tapered roller bearings (P6 and P7).
The test-rig was equipped by several accelerometers located in different positions of the traction system. The vibration signals were acquired by a Data Acquisition System (DASY) which is composed of a National Instruments PXI module placed in the test-rig room and connected to a remote desktop PC by means of a fiber-optic cable able to convey a large amount of data with a high sample frequency, that was set to 20 kHz.

3. Experimental test conditions

A batch of experimental tests was performed for each configuration or set of bearings (i.e. combination of new or worn bearings in positions Pn), during the experimental campaign. The batch was composed of tests at different conditions of train speed and traction motor torque, in order to consider a wide range of train operating conditions (i.e. acceleration, braking and cruise). Therefore, each set of bearings was tested by following the scheme shown in Figure 2.

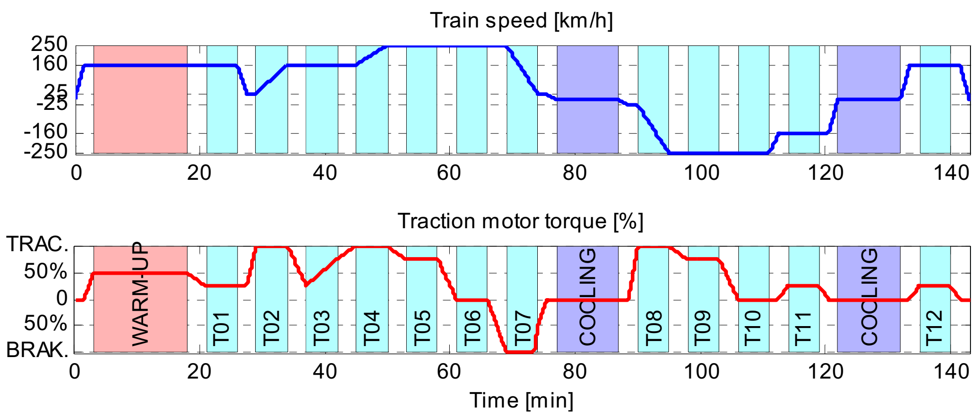


Figure 2: Operating conditions (train speed and motor torque)

All the batches of the experimental campaign started with a warm-up phase, performed at 160 km/h and at 50 % of relative motor torque, in order to have the same operating conditions and to reach an adequate lubricant temperature. The warm-up phase was followed by a series of 12 tests Tm at different operating points. Each test lasted 300 s, during which DASY acquired data for 180 s. Moreover, 2 cooling rests of 10 minutes were set between test T7 and T8 and between test T11 and T12, when the rotation direction is inverted. Furthermore, test T12 is a check test, with the same parameters of test T1. For the sake of brevity, the results obtained for all the tests of a certain configuration of bearings will not be discussed: only the signals measured during the final test (i.e. T12) will be reported in the following, which operating parameters are listed in Table 1.

Table 1: Parameters of operating condition of test T12

Parameter	Value
Train speed [km/h]	160
Motor rotational speed [rpm]	3170
Motor rotational torque [% of the available torque]	25
Wheel shaft rotational speed [rpm]	970

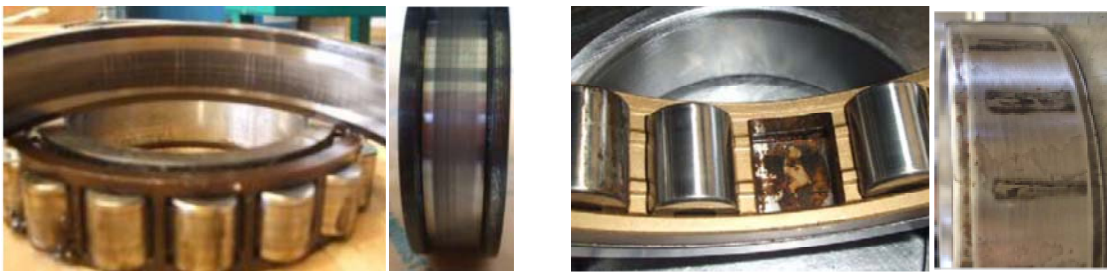
4. Results of experimental tests

Bearings for HST applications have to maintain constant conditions, without degradation for about 3 millions of km for HST applications. However, some defects may appear in the bearings after years of service. Both artificially damaged and worn bearings, taken from the service, were installed and tested. In particular the following configurations will be considered in this paper, whereas the geometrical dimensions of the considered bearings are listed in Table 2:

a) Configuration ①: worn roller bearing for the DE side of the motor (Figure 3(a));
b) Configuration ②: worn roller bearing for the DE side of the gearbox high speed shaft (Figure 3(b)).

Table 2: Geometrical parameters of the worn bearings.

	Configuration	
	①	②
Inner ring diameter [mm]	83.5	88.5
Outer ring diameter [mm]	113.5	118.5
Rolling element diameter [mm]	15	15
Pitch diameter [mm]	98.5	103.5
Rolling element number	17	18
Contact angle [deg.]	0	0



(a) (b)

Figure 3: Cylindrical roller bearings taken from the service: (a) configuration ① - bearing at the DE side of the traction motor; (b) configuration ② - bearing at the high speed shaft of the HST gearbox.

The analysis of the raw signals by means of statistical parameters does not allow the detection of possible faults and the characterization of the bearing condition. It is widely accepted in literature and in the industrial field that, owing to the phenomena involved in bearing functioning and to environmental noise, vibration signal analysis by simple Fourier Transform is not effective for the detection of bearing damages. For these reasons, the more sophisticated signal processing technique as the spectral kurtosis has been used. Given that the application of spectral kurtosis to vibration signals of the *reference configuration* (i.e. all new bearings installed in positions P*n*) shows harmonic components only related to the good functioning of the HST traction system for all the sensors, for the sake of brevity only the results of the configurations with damaged bearings will be shown in the following.

4.1 Configuration ①: bearing on motor DE side

The cylindrical roller bearing taken from the service and supporting the HST motor shaft on the DE side is shown in Figure 3(a). The cage and the rolling elements are clearly visible in Figure 3(a); it is also possible to see the small amount of grease on the rolling elements. Therefore, the condition of reduced lubrication can be assumed. Moreover, the rolling elements are characterized by circumferential lines indicating bearing wear. The raceway of the outer ring is characterized by localized signs, which are likely due to localized spalling.

The application of SK to the signal measured by sensor A1 (Figure 4(a)) for the damage configuration ① allows highlighting the first 5 harmonics of the ball passing frequency on the outer ring (theoretical BPFO = 381 Hz), each of them characterized by the presence of sidebands spaced by the cage or fundamental train frequency (theoretical FTF = 22.4 Hz). These harmonic components clearly indicate the presence of damages on the outer ring of the bearing: the high number of harmonics and the presence of FTF sidebands suggest that outer race is damaged in many points: this is actually the effect of an impulse train. The results are not so clear for sensor A2 placed on the motor case. Figure 4(b) shows that the only relevant components in the SK analysis are 1X and 2X of BPFO. Sidebands are evident only for 1X of BPFO. The difficulty of diagnosing the damage can be ascribed in this case to the position of the accelerometer.

For the considered traction system, the diagnosis of bearing motor is possible by using sensors installed close to the bearing, even if not necessarily in the load direction (the horizontal x direction was used). This is relevant because motor installation in the bogie is rather cramped and sensors have also to be protected by accidental impacts of stones or objects, therefore sensor position could be often selected on the simple basis of space for its safe mounting.

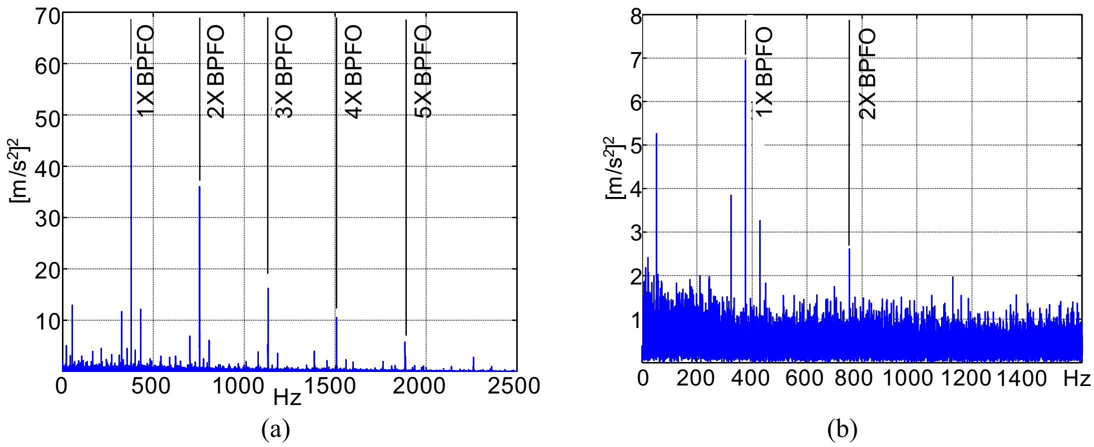


Figure 4: Spectral kurtosis results for vibration signals of configuration ① measured along x direction by (a) accelerometer A1 placed close to the bearing and (b) accelerometer A2 placed on the case of the motor

4.2 Configuration ②: bearing on gearbox DE side

The second case considers a cylindrical roller bearing supporting the high speed shaft of the gearbox. The worn bearing, taken from the service, is shown in Figure 3(b). Oxidation of the bearing components has been detected during the inspection performed after the batch of tests. Also in this case the oxidation may be due to oil contamination.

The vibration signals were acquired along the z direction by the tri-axial accelerometer A5, placed on the case of the gearbox close to the bearing, and by the tri-axial accelerometer A4, placed on the case of the gearbox far from the bearing. Figure 5 shows the results of the application of SK for the raw signals of the two accelerometers. SK analysis highlights the first 3 harmonics of the cage rotation (FTF = 22.6 Hz) and the first 6 harmonics of the frequency of the passage of rolling elements on the outer ring (BPFO = 400 Hz) for accelerometer A5 (Figure 5(a)). In this case, the components related to the motion of the train of rolling elements dominate SK frequency distribution, conversely from the oxidation on the ball bearing of case ②.Similar results are obtained for accelerometer A4 (Figure 5(b)), but only with the first three harmonics of BPFO. The reduction of the energy related to both the FTF and the BPFO harmonics, with respect to the accelerometer A5, is probably due to the fact that the sensor is far from the bearing in this case.

Results of this and previous section prove that the diagnosis of bearing faults on the gearbox of this traction system is possible even using an accelerometer installed far from the bearings. This suggests that a reduced number of sensors can be used on the gearbox.

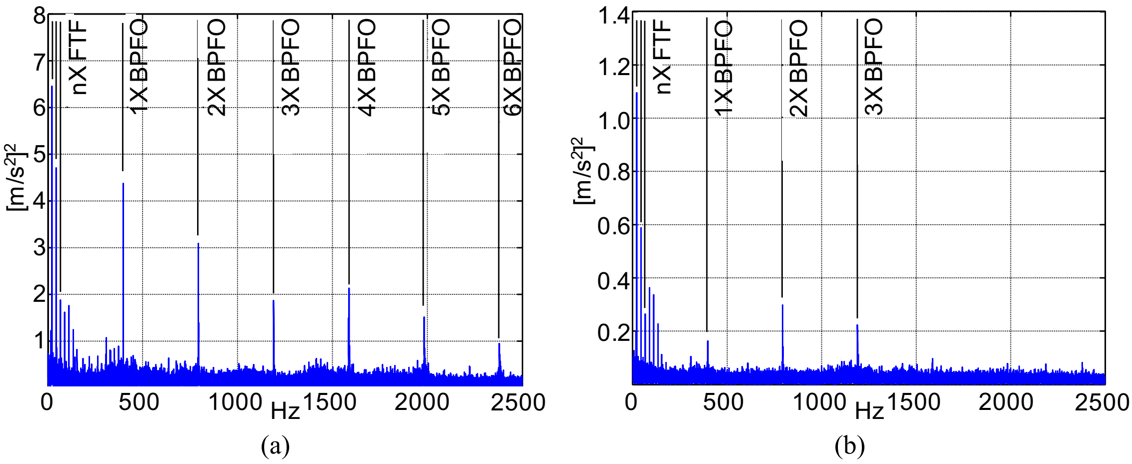


Figure 5: Spectral Kurtosis results for vibration signals of configurations ② measured along z direction by (a) accelerometer A5 placed close to the bearing and (b) accelerometer A4 placed far from the bearing

5. Conclusions

In the paper the experimental results obtained by a full-scale test-rig for the diagnosis of bearing dameges in the traction system of high speed trains has been described. The test-rig is equipped with real HST motor and gearbox and it is able to reproduce the harsh and noisy operating environment, owing to wheel-track interaction. The test-rig has been used to test several bearings in different conditions in order to tune the signal processing algorithms for bearing diagnostics and select the most suitable positions for the sensors. In this paper, the results obtained for bearings taken from the service, which are more interesting from an industrial point of view, have been discussed.

In order to define the bearing condition, the vibration signals were processed by a properly tuned spectral kurtosis algorithm. In all the cases, the algorithm has allowed the detection of the faults affecting the bearings. The sensitivity analysis on sensor positions, performed during the experimental campaign, has proven that, in some cases, sensors placed far from the damaged bearing are suitable for fault diagnostics. In this way, the number of sensors to be employed for the diagnostics of the HST traction system can be reduced, with consequent reduction of system complexity and cost.

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