Vibrations analysis of bogie’s axle from an electric locomotive class 43

M Alexandrov¹, V Goanță², V Paleu²*, D Apostol¹ and M Atanasiu³,

¹CFR society, Iasi branch, Iasi, Romania
¹Mechanical Engineering, Mechatronics and Robotics Department, “Gheorghe Asachi” Technical University of Iasi, Iasi, Romania

E-mail: vpaleu@tuiasi.ro

Abstract. Reliability and maintenance play an important role in the field of rail vehicle systems. In order to be reliable, this type of transport needs continuous monitoring and regular maintenance. Regarding requested repair and maintenance interventions in relation to the probability of failure for each component, assembly or subassembly, additional information could be taken by data acquisition from sensors fitted to the locomotive bogies. The influence of the rail pattern configuration and the asymmetry of the positioning of both the traction motors and the gearbox on the amplitude and frequency of the introduced vibrations is considered. Fast and robust online signal processing algorithms are essential for designing a smart device. In this way, maintenance models can be created based on the state of the systems and integrated platforms can be produced in order to improve the diagnosis and expertise of a maintenance program. The paper presents the method of determining the vibrations induced by various causes at one of the axles of the electric locomotive class 43, of 3400 kW (4620 hp), focusing on rolling bearings fault frequencies. Further research will aim to detect the other possible sources of vibrations transmitted at the bogie’s axle.

1. Introduction

The railway axles are composed of three main components: wheels, axle and axle bearings. Faults can occur on any of the components mentioned above, but the most common ones are related to axle-mounted bearing damage. Continuous increase in train operating speed may result in the failure of an axle bearing, which can drive to very serious derailments that can cause human casualties, severe infrastructure disruptions, impaired running, unnecessary costs and loss of confidence in rail transport. The railway industry has focused on improving online maintenance and monitoring conditions of rolling stock to minimize the probability of failure [1].

Rail transport is increasingly required on the transport market because it is safe, fast and much less polluting compared to other transport systems. The wheels of rolling stock operate under high load conditions and high axle speed. In addition, use in difficult environmental conditions requires rigorous and reliable maintenance and inspection [2]. In operation, the wheel sets function under difficult conditions, including contact fatigue, thermal variations and shock loading [3]. The gradual deterioration of the structural integrity of the wheels and axle bearings can increase the risk of failure and, consequently, the possibility of unnecessary delays, costs and derailments, increased levels of vibration, noise and temperature produced by the axle-mounted bearing [4].
Within the framework of structural integrity monitoring, vibrations are defined as the generation of elastic waves achieved by a sudden redistribution of atoms inside or on the surface of a material. When an external stimulus, such as temperature or load, is applied to a material, the energy released will be in the form of a voltage wave. These waves can be detected using piezoelectric sensors. In recent years, progress has been made in predictive online maintenance of rotary machines in the oil and gas and maritime industries. These advances have led to the development of a reliable technique based mainly on the trend of vibration signals and sometimes vibration waveforms [5]. Therefore, in the railway industry the bearings on the axles are considered as a critical component of the rolling stock [6].

The bearings of a set of wheels support some of the weight of the vehicle as the wheel rotates. If a bearing is faulty, the corresponding wheel will lock. However, the other wheel continues rotating. Due to the abnormal movement of the wheel set caused by the locked wheel, the axle may break, eventually causing the train to derail.

Defects in axle bearings can be classified as distributed or local. Distributed faults, such as surface roughness, ripple etc., and the variation of the contact force between the rolling elements can increase the level of vibration and noise produced by the bearing on the axle [6]. Localized defects, such as cracks, pitting, tips etc., can generate mechanical impulses that can give rise to short-term vibrations or acoustic signals [5].

Usually, when an impact occurs in a defective rolling element, an impulse will occur. This impact will produce an excitation of characteristic frequencies of the structure [1]. The main idea of the signal analysis technique is to detect and eliminate the influence of the disturbances. In practical applications, the characteristic frequency may vary due to different types of bearings. Signal frequency analysis is an efficient method to detect rolling bearings with faults, but when the faults are evident [7].

This article presents the results of vibration measurements performed on one of the axles of the electric locomotive EC043. In order to detect and diagnose the vibrations induced by various mechanisms in the axle of a locomotive bogie, in this paper the authors monitored and processed the signals acquired from the vibration sensors mounted in the vicinity of one bearing of bogie’s axle. By mean of Fast Fourier Transform (FFT), correlation and cross-correlation of the acquired signals, both frequency and time analysis methods were employed. The results focused on rolling bearings fault frequencies, further research on other possible sources of vibrations being in development.

The bearings on the axle were changed at the time of maintenance on the locomotive. About 5 months after the respective maintenance was done, at the end of one of the axles two vibration sensors were mounted, one acquiring data on vibrations in the vertical direction and the other on the horizontal direction, both connected to the Microlog MX device. The analysis of the vibration signals was used as an effective tool to detect and evaluate both the deterioration of the bearings considered in this study and the vibrations introduced in the axle by different disturbing factors. From the results obtained it can be concluded that, by analyzing the variation of the vibration signals, we can evaluate the bearings’ running state and axes’ induced vibrations by characteristic frequencies of corresponding defects under real operating conditions.

2. Data acquisition system and experimental setup
The acquisition of the signals from the vibration sensors was performed with Microlog analyzer type SKF CMXA 75-M-K-SL. With the aim to detect all possible induced vibration modes in the axle, vibrations analysis range spanned between 16 Hz și 20 kHz.

With within the acquisition program, the vibration sensors were mounted in the immediate vicinity of one of the locomotive axle-end near the bearing, figure 1. One of the sensors captured the vibrations wave in the vertical direction and the other in the horizontal direction. The sensors (accelerometers of type IMI-1430-3, sensitivity 101 mV/g) were fixed by magnetic supports. The SKF Microlog vibration analyzer acquired data from accelerometers from the locomotive cab. Data acquisition frequencies were varied from 5000 Hz to 40 000 Hz.
Figure 1. Mounting the sensors and connecting to the SKF device.

The double row spherical roller bearing from the axle’s end is from 23234CC-3L series and has the geometrical parameters presented in Table 1. The rolling bearings were replaced during a general maintenance operation of the locomotive that took place 6 months ago, so for this experiment they should be relatively as new. Anyway, the obtained subsequent results proved that most of vibrations induced to axle are from other mechanisms.

Table 1. Geometrical parameters of double row spherical roller bearing - 23234CC-3L series.

| No. | Diagnosed mechanism | Characteristics                          |
|-----|---------------------|-----------------------------------------|
| 1.  | Rolling bearings    | number of rollers on each row, Z=18     |
|     | 23234 series (double row spherical roller bearings) | roller diameter, Dw=34.52 mm |
|     |                     | inner ring diameter, d=170 mm           |
|     |                     | outer ring diameter, D=310 mm           |
|     |                     | bearing width, B=110 mm                 |

At a constant speed of 70 km/h, the electric traction motor speed is 2500 rpm, that is a rotational frequency of 41.66 Hz. The reduction gearbox has a transmission ratio of 3.65, resulting a speed of the axle of around 685 rpm and a rotational frequency of 11.42 Hz. The speed of compressor is 3000 rpm. There are some supplementary mechanisms, as worm gears and belt transmission of compressor, and elastic joint between the electrical motor and gearbox, not considered in this analysis.

The temperature developed on the hub of the rolling bearing was measured along all the way by T650 SC Thermovision camera. In this study, we are focusing just on rolling bearings vibrations, trying to detect their fault frequencies – if any, in such a complex vibrating structure.

3. Results

3.1. Signal processing technique

The amplitude-time signal was obtained from the two accelerometers of SKF analyzer, a representation of a signal sample being presented in figure 2a. Even the SKF analyzer can realize the FFT, we processed the signals in both time and frequency domains using LabVIEW software. The next information is obtained from our LabVIEW software:
- Signal representation in amplitude-time coordinates, x(t), figure 2a.
- The Fast Fourier Transform (FFT) of the input sequence x(t), that is the amplitude-frequency spectrum, figure 2b. It offers information about the characteristic frequencies contained in the vibrational signal.
- The Histogram of the acquired signal, figure 2c. It groups samples within the same range of amplitude values, having specific forms for Gaussian noise (the bell shape) and periodic shape for sinusoidal signals.
- Autocorrelation function, Rxx - computes the normal or partial auto-correlation value of a univariate time series, comparing the signal with itself at different periods. If there is a vibration signal in noise, the autocorrelation function will detect it better than the FFT does it. If the signal contains only white noise, the autocorrelation function will take a huge value just in zero-time displacement of signal. For periodic signals, the autocorrelation will be also periodic, having the same sampling period as the original signal [8].

In the above example of figure 2b, it can be observed from FFT result that there is an obtained main frequency around 50 Hz with higher amplitude, corresponding to the frequency associated to the compressor main speed. As shown in the next examples, the amplitude-frequency spectra are different from a moment of time to another one, but there are some repeating constant peaks of frequencies, one of this being that due to compressor.
The histogram (figure 2c) shows that the data presented a Skewness of 0.076 and a Kurtosis of 2.46. For pure Gaussian signals (noise), the histogram has a skew factor of 0 and Kurtosis is 3. It seems that our signal contains a lot of noise, but autocorrelation function, Rxx (figure 2d) proves that there is a periodic signal hidden in the overall noise, the Rxx form having a low central peak and modeling a periodic wave too, with the same main frequency of 50 Hz.

Statistical parameters are presented in LabVIEW interface (right side of figure 2). The signal-to-noise ratio (SNR), obtained as the ratio of arithmetic mean and standard deviation of signal samples, is about 2, proving the quality and certainty of data acquisition. Once again, SNR value shows that there is a measurable vibrational signal with an offset, the arithmetic mean of the signal being two times greater than the standard deviation (signal fluctuation around the mean value). Standard deviation is almost nil, but is different from the root mean square (RMS). It means once again that the overall measured level of vibration is higher than the perturbation signal (undesired noise) [5].

**Figure 2.** Data processing in LabVIEW.
3.2. Experimental results for rolling bearing diagnosis

A second LabVIEW virtual instrument was developed to compute the natural frequencies of the rolling bearings (figure 3). A constant speed of the train was kept, \( v_T = 70 \) Km/h, the traction electrical motor speed being 2500 rpm.

The presence of a defect in the axle bearings will lead to significant changes in vibration modes, signalized by appearance of important amplitude values of the so-called fault frequencies. Vibration analysis is a useful technique for continuous and efficient monitoring of both the state of the bearings and the elements that introduce dynamic loads. In the early stages of the evolution of an axle bearing defect, the chance of reliably detecting using conventional spectral analysis (FFT) is low.

Any bearing defects on the axle, unless it is detected in time, will almost certainly worsen, before the final catastrophic failure occurs.

Next fault frequencies are computed [8]:
- FTF - Fundamental Train Frequency - frequency emitted by a faulty or unbalanced cage;
- RPFI - Rolling element Pass Frequency of Inner Ring - frequency emitted by a rolling element impacting a defect on inner race surface, usually a pitting;
- RPFO – Rolling element Pass Frequency of Outer Race - frequency emitted by a rolling element impacting a defect on outer race surface;
- RSF – (Rolling element Spin Frequency) – frequency emitted when a rolling element bearing with a surface defect pass over the inner or outer races.

The amplitude-frequency spectrum of a faulty rolling bearing may also include not only the above mentioned fault frequencies, but also the sidebands resulted from amplitude modulation (figure 4). Such sidebands may appear to inner and outer races frequencies and to cage rotation frequency [8].

Figure 3. Fault frequencies computation in LabVIEW.

Figure 4. Measured fault frequencies: (a) vertical; (b) horizontal.
Temperature measurement on the hub of the rolling bearing was realized by T650 SC Thermovision camera. Significant results are presented in figure 5.

![Thermovision camera](image)

**Figure 5.** Measured bearing hub temperatures: (a) image of the thermovision camera; (b) starting temperature; (c) intermediate temperature; (d) highest measured temperature.

The maximum developed temperature on the bearing’s hub remains at a low level, below 30°C. It must be noticed that the start temperature, measured also on the bearing’s hub, was about 17.3°C, and the maximum recorded temperature was about 29°C. Nevertheless, the temperature was monitored far from the inside of the bearing, most of the heat being dissipated by conduction in the bearings assembly (axle, wheel, and house – bogie). The relatively low temperature developed within the bearing, correlated with vibration analysis results, indicates that the possible fault of the bearing is still in an incipient stage.

4. Conclusions

The aim of the study is to monitor the vibrations level and the temperature of a rolling bearing from the axle of the bogie of a locomotive during its usual trip on the route Iasi – Pascani.

Two accelerometers were mounted on the house of a rolling bearing from the axle of locomotive bogie, one in vertical position and the other in horizontal position. A thermovision camera monitored the developed temperature of bearing’s hub.

Statistical and frequency domain signal processing techniques were employed: Histogram, autocorrelation, SNR, RMS, and FFT, respectively.

Preliminary results showed that the rolling bearing presented faults, especially at the inner ring level (a possible pit). The cause of the faults may be:

- Improper storage or / and improper lubrication;
- Improper mounting;
- Bad quality of the steel;
- Improper thermo-chemical treatments.

The developed temperature on the bearing’s hub remains at a low level, up to 30°C. It means that the possible fault of the bearing is still in an incipient stage.
5. References

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