Vibration analysis for fault diagnosis of rolling element bearings

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Abstract: Bearing failure is often attributed to be one of the major causes of breakdown in industrial rotating machines that operate at high and low speeds. In this work we have used some of the modern techniques of vibration analysis included today in some commercial vibration analyzers. For the experimental study, good shape ball bearings and localized defect in the outer race ball bearings, were tested under different levels of fault severity and various load and speed conditions. Normal spectral analysis, demodulation, PeakVue and real zoom analysis were the techniques used for the analysis.

[Ebrahim Ebrahimi . **Vibration analysis for fault diagnosis of rolling element bearings.** .Journal of American Science 2012;8(2):331-336]. (ISSN: 1545-1003). http://www.americanscience.org. 47

Key Words: Condition Monitoring - Low Speed Machinery - Rolling Element Bearings - Vibration Measurements

1.Introduction

A variety of analysis methods exist for condition monitoring of bearings including: vibration analysis, oil analysis, infrared thermography and motor current signature analysis. Between these methods, vibration analysis is the most commonly used method and the one that provides the most information from the data acquired. Investigating the statistical parameters derived from the time domain signals is the simplest vibration analysis technique. It has been shown that vibration signals from good and defective bearings manifest statistically different behaviors in the time domain, such as different peak, root-mean square (rms), crest factor, kurtosis, skewness values and cyclic spectral analysis [1,2,3,4,5, 24].

Rolling element bearings have time-varying stiffness characteristics and periodic impulses are generated as the rollers pass over bearing defects with a frequency that is characteristic of the defective element. High frequency resonance analysis (also known as envelope analysis) and frequency domain methods have been used for the identification of these major frequency components in the vibration spectrum for detecting localized defects[6,7,8]. Advanced techniques such as time-frequency analysis and the wavelet transform, neural networks and recently hidden Markov models have also been employed in machinery vibration analysis. Nevertheless, especially as a machine fails, the vibration characteristics of the machine are changing and nonlinear dynamical analysis techniques may be the most suitable methods for various aspects of machinery analysis including fault detection and diagnosis[9,10,11,12,13,14,15].

The objective of the signal analysis is the discovery of discriminative features that allow the identification of problems in their early stages. In particular, bearing problems manifest in alterations of the vibration patterns of the machines. Especially for defects in rolling element bearings envelope detection] is an indicated technique because the mechanic defects in components of the bearing manifest themselves in periodic beatings, overlapping the low frequency vibrations of the entire equipment, for instance caused by unbalance of the rotor of the pump. The Hilbert transform plays an important role in the sequence of steps of the analysis. The main idea is the separation of the defect frequency and the natural frequency of the beating by demodulation[16,17].

The process of roller bearing fault diagnosis includes the acquisition of information, extracting feature and recognizing conditions. The later two are the priority. Different methods are used for the acquisition of information; they may be broadly classified as vibration and acoustic measurements, temperature measurements and wear debris analysis. Among these, vibration measurements are commonly used in the condition monitoring and diagnostics of the rotating machinery . The vibration measurement of the roller bearing can be made using some accelerate sensors that are placed on the bearing house. When faults occur in the roller bearing, the vibration signal of the roller bearing would be different from the signal under the normal state [18,19,20,21,22,23].

In this work we have used some of the modern techniques of vibration analysis included today in some commercial vibration analyzers. For the experimental study, good shape ball bearings and localized defect in the outer race ball bearings, were tested under different levels of fault severity and various load and speed conditions.

2. VIBRATION ANALYSIS IN ROTATING MACHINES

Rotating machines , due to the rotating nature of their internal pieces, produce vibrations. Accelerometers strategically placed at points next to bearings and motors allow the displacement, velocity or acceleration of the machine over time to be measured, thus generating a discrete signal of the vibration level. In general, the orientations of the sensors follow the three main axes of the machine, that is, vertical, horizontal, and axial.

In the presence of bearing defects there are vibrations that overlap the signals of normal operation conditions. Besides that, faults from other problems of the machinery can also occur. An example are the lower frequency vibrations which typically occur in case of unbalance of the rotating parts of the pump. Whenever a collision between a defect and some bearing element happens, a short duration pulse is produced. This pulse excites the natural frequency of the bearing, resulting in an increase of the vibration energy.

The structure of a rolling bearing allows establishing a model of possible faults. Fig. 1 illustrates a basic model of a bearing with the rolling elements, the inner and outer raceways, and the cage. The bearings, when defective, present characteristic frequencies depending on the localization of the defect . Defects in rolling bearings can be foreseen by the analysis of vibrations, detecting spectral components with the frequencies (and their harmonics) typical for the fault. There are five characteristic frequencies at which faults can occur. They are the shaft rotational frequency FS, fundamental cage frequency FC, ball pass inner raceway frequency FBPI, ball pass outer raceway frequency FBPO, and the ball spin frequency FB. The characteristic fault frequencies, for a bearing with stationary outer race, can be calculated by the following equations [25]:

$$F_{\downarrow}c = 1/2\ F_{\downarrow}s\ (1 - (D_{\downarrow}b\cos(\theta))/D_{\downarrow}c\ \ )$$

$$F_{\downarrow}BPI = N_{\downarrow}B/2\ F_{\downarrow}s\ (1 + (D_{\downarrow}b\cos(\theta))/D_{\downarrow}c\ \ )$$

$$F_{\downarrow}BPD = N_{\downarrow}B/2\ F_{\downarrow}s\ (1 - (D_{\downarrow}b\cos(\theta))/D_{\downarrow}c\ \ )$$

$$F_B = \frac{D_c}{2D_b} F_s \left(1 - \frac{D_c^2 \cos^2(\theta)}{D_c^2}\right)$$

where Db is the ball diameter, q is the load angle based on the ratio of axial to radial load, Dc is the cage diameter, and Nb is the number of balls. These equations consider that the rolling elements do not slide, but roll over the race's surfaces. Of course, there is virtually always some slip and these equations give a theoretical estimate which would vary by 1-2% from the actual values . These frequencies will only be present in the vibration spectrum when the bearings are really defective or, at least, when their components are subject to tensions and deformations that can induce a fault[26].

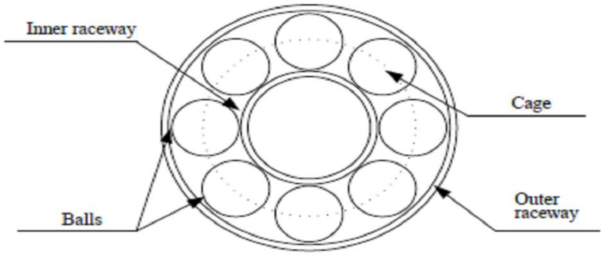

Figure 1: Sectional view of a bearing model [25]

There are a number of factors that contribute to the complexity of the bearing signature that could not be simulated but must be taken into consideration. Only with real data it is possible to work under real environment conditions. We will show and analyze some real examples to illustrate how the theory appears in practice. First of all, variations of the bearing geometry and assembly make it impossible to precisely determine bearing characteristics frequencies. The fault severity progress can alter the bearing geometry, contributing to the increase of complexity of the diagnosis process. Operating speed and loads of the shaft greatly affect the way and the amount a machine vibrates causing bearing basic frequencies to deviate from the calculated value. In a real-world environment, the motor speed cannot keep rotating at a constant FS precisely. This fluctuation can be caused by external factors such as the performance of the controller, noise, and disturbance in the power system. It is important to consider band frequency range around the characteristic frequencies. Consequently these range needs to be large enough to solve this problem without creating another one. Fault signature appear to be very different at advanced stages of severity. As the bearing gets worse the number of sidebands increase. What may have started out as a relatively sharp peak may appear to be spreading out to cover a wider frequency range. The raise of sidebands can be seen in Fig. 2 indicating that the condition of this bearing is worsening.

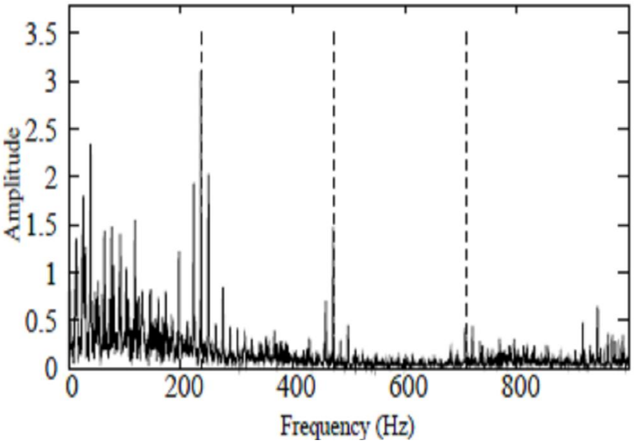

Figure 2: *F*C sidebands around *F*BPO harmonics

3.Diagnosis techniques

To detect a defect in an early fault stage, different techniques and instruments have been developed depending on the range of frequencies within which the vibration analysis will be carried out. Some techniques have the high range frequency analysis approach; others have the medium and low range approach. The techniques which analyze the high frequency zone are based on the excitation of the natural frequency of the sensor, bearing parts and housing structures due to when such a defect on one surface strikes its mating surface, a pulse of short duration is produced. When the bearing rotates with a constant rotational speed, these pulses are generated periodically and the frequency is the characteristic defect frequency.

4.Envelope Analysis for Diagnostics of Local Faults in Rolling Element Bearings

Envelope Detection or Amplitude Demodulation is the technique of extracting the modulating signal from an amplitude-modulated signal. The result is the time history of the modulating signal. This signal may be studied as it is in the time domain or it may be subjected to a subsequent frequency analysis. Envelope Analysis is the FFT (Fast Fourier Transform) frequency spectrum of the modulating signal. Envelope Analysis can be used for diagnostics/investigation of machinery where faults have an amplitude modulating effect on the characteristic frequencies of the machinery. Examples include faults in gearboxes, turbines and induction motors. Envelope Analysis is also an excellent tool for diagnostics of local faults like cracks in Rolling Element Bearings (REB). The envelope spectra for various types of bearing defects obtained by FFT with ED are shown in Fig. 3. Fig. 3(a) shows the spectrum of the enveloped signal for bearing with outer race defect. From the spectrum the impact repetition, frequency at 86.6 Hz and its second harmonic at 173 Hz can be clearly recognized. The frequency 86.6 Hz is very close to the calculated BPFO at 86.5 Hz as listed in table 1. Hence, the defect is identified as outer-race defect. In Fig 3(b) the impact repetition frequency at 144 Hz can be recognized however; its second harmonic at 288 Hz is not very evident. As the frequency 144 Hz is very close to the calculated BPFI at 144.3 Hz, hence the defect can be identified as inner-race defect. By inspection of Fig. 3(c) ball defect can also be identified as the impact repetition frequency at 108 Hz can be recognized as well as the second harmonic at 216 Hz.

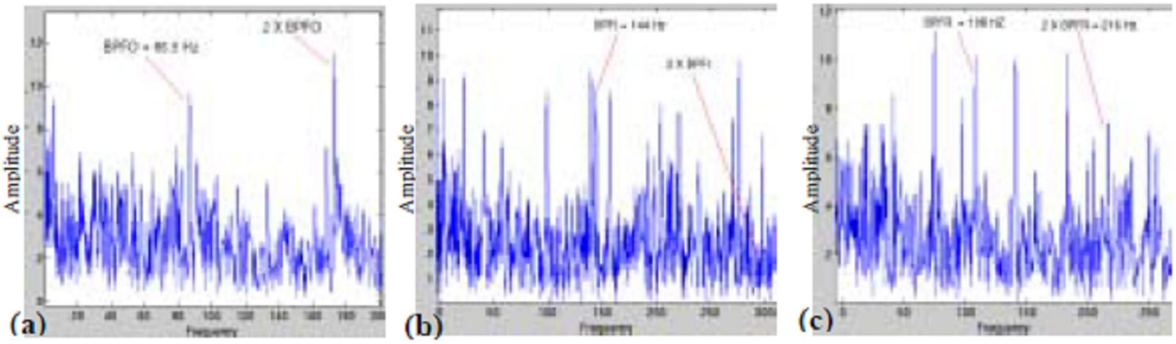

Fig. 3: (a) Envelope spectrum of bearing with outer-race defect (b) Envelope spectrum of bearing with inner-race defect (c) Envelope spectrum of bearing with ball defect

5.Time Frequency Analysis

A number of time frequency have been developed which show potential for detecting bearing problems in some of the more complex classes of rotating machines where the signal to noise ratio is low and a large number of frequency components are present. These techniques include the short time Fourier transform (STFT), wingerville distribution (and variance) and the wavelet transform. Bearing resonance signatures are first demodulated by using wavelet analysis, then the resulting wavelet energy functions are integrated to enhance feature characteristics, and finally, a correlation spectrum is employed to highlight bearing-fault-related feature characteristics. time-frequency analysis technique, combined with kurtosis method and wavelet analysis have been used for the detection and diagnosis of the faults based on the unstable vibration signals from the rolling bearings. With this method, the signals were decomposed and reconstructed by the wavelet analysis, followed by the analysis of demodulation and spectral refining by using Hilbert transformation. The experiment results show that the fault information of the rolling bearings can be detected and diagnosed effectively, which favor the quick determination of the detailed faulty type within the bearings .various signal processing techniques were applied to the vibration signal (STFT, Welch periodogram, cepstrum and envelope analysis). Even the scalar quantities (crest factor, kurtosis) were not determinant in the identification of the faulted bearing. The obtained results proved that it is very hard to find a single characteristic quantity that states the health condition of the bearing. Indeed the results obtained by the FFT alone and simple envelope analysis were the most relevant ones and then they were reported in the paper. Induction motor vibrations, caused by bearing defects, result in the modulation of the stator current.

6.Conclusion

In this study, diagnosing techniques of the ball and cylindrical roller element bearing defects were investigated by vibration monitoring and spectral analysis as a predictive maintenance tool. Ball bearing looseness, a ball bearing outer race defect and a cylindrical bearing outer race defect were successfully diagnosed. It was shown that ball and cylindrical roller bearing defects were progressed in identical manner without depending on rolling element type. Furthermore, it was experienced that when a bearing defect reaches an advanced stage, high frequency amplitude levels often decrease due to ‘self-peening’ of the bearing flaws. Remaining life of the bearings can be estimated using vibrational behavior and running time of the bearings. Diagnosing of defects on multiple parts of the bearing may also be investigated in a real running condition. Also, it can be concluded that if vibration. monitoring is applied within regular selected periods, capable instrumentation and if vibration analysis is performed by experienced personnel, impending failures can be easily detected. However, the faults caused by defective inner-race and rollers are more difficult to identify by FFT with ED technique. On the other hand, when using the time-frequency distribution diagrams provided by WA, the high-energy impacts caused by inner-race and ball defects can be easily identified in the high frequency bearing excitation ranges.

Acknowledgements

The authors would like to thank Islamic Azad University, Kermanshah Branch for its support to this research.

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1/25/2012