ICMIEE20-084

Vibration Analysis of Rolling Element Bearing using Micro Electro-Mechanical System (MEMS) Based Accelerometer

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ABSTRACT
Rolling element bearing is a common machine element which often leads to unexpected machine breakdown in case of its failure. Vibration analysis has long been studied for early bearing fault detection to prevent this type of costly damage. However, these studies often used expensive sensors and data acquisition systems. In the present study, a cost-efficient method was developed to extract and analyze vibration signals from a bearing and detect the bearing fault. To extract the signal, an experimental setup was built with one new healthy bearing and one randomly damaged bearing by mounting them on a shaft. The vibration signal was obtained using a tri-axial Micro-Electro-Mechanical System (MEMS) based accelerometer. An Arduino based microcontroller platform was used to acquire sensor data and send it to the computer via serial communication for further processing. For signal processing, High-Frequency Resonance Technique (HFRT) was applied. The envelope spectrum of the raw vibration signal was calculated to find the characteristic frequency of the system. Distinctive fault characteristic frequencies were obtained from the damaged bearing. This result shows that bearing condition can be effectively monitored by analyzing vibration data captured from a MEMS accelerometer.

Keywords: Vibration Analysis, Micro Electro Mechanical System (MEMS), High-Frequency Resonance Technique (HFRT), Rolling Element Bearing, Bearing Fault Detection

1. Introduction

Bearing failure is a common phenomenon that impacts turbomachinery performance and causes financial losses in factories as well as plants. It has been shown that vibration monitoring is an efficient method to determine the condition of the bearing and avoid its failure in advance [1]. Many experiments have been undertaken to explain the vibration signature in the ball bearings originated due to their defects [1-8]. Bearing failure can occur for many reasons, including excessive loads, misalignment of the shaft, inadequate lubrication, etc. This fault can be originated in any part of a bearing, like external race, inner race or ball elements. They are initially single point defects or localized defects that stimulate resonance with the bearing structure at certain characteristic resonant frequencies [2-3]. McFadden and Smith (1983) developed a model for single point defect under constant radial load [9]. Identifying the fault characteristic frequency correctly is always a huge concern as the vibration signals are highly submerged in machine noise. Randall & Antoni (2011) reviewed some common methods for separating bearing vibration signal from noise and enhancing of that signal [4]. The model of Randall is helpful to detect the frequency of bearing from the surreal frequency of other elements. A well-developed algorithm, spectral kurtosis, along with a minimal entropy deconvolution, is explained in [5] that can extract the actual frequency buried in noise. High Frequency Resonance Technique (HFRT) is another significant method to detect ball bearing failures in turbomachinery [6]. This approach is also considered to be compatible with commercial use since it can efficiently disregard the background noise, as stated in the review articles [7]. In this process, the raw vibration signal is analyzed to find a resonance frequency, at which the signal is modulated by bearing defect frequency as derived in [8]. These frequencies are known as ball pass frequencies. There are four types of ball pass frequencies depending on the structure of the bearing, namely Ball Pass Frequency Outer (BPFO), Ball Pass Frequency Inner (BPFI), Fundamental Train Frequency (FTF) and Ball Spin Frequency (BSF). Generally, the resonance in the bearing structure is induced if any components of the bearing hit the fault location. This resonance is found to be in the high frequency region (>1 kHz) [12]. The envelope spectrum of the modulated signal is then calculated and analyzed. This spectrum shows a high energy level at the harmonics of defect frequency which can be used to diagnose the fault in the bearing.

Literature surveys show that previously developed vibration monitoring systems require high-cost industrial grade piezo-electric transducer-based accelerometer as well as high speed data acquisition

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systems. With the technical advancement, low-cost accelerometer based on the Micro Electro-Mechanical System (MEMS) has been introduced. Due to their advantages researchers have been studying the possibility of using them for vibration monitoring purposes. However, very few studies are available on their uses in bearing vibration monitoring. The authors [10-11] developed a data acquisition method using the MEMS accelerometer and microcontroller to monitor vibration in motor. In [11], the authors used this setup to measure the vibration level in the induction motor and detect anomaly in its operation. In this present research, a novel approach of combining MEMS accelerometer and HFRT based bearing vibration monitoring system was tested experimentally. The authors discussed the applicability of this system for fault detection of rolling element bearing in industries.

2. Methodology

An experimental setup was built with one healthy and one randomly damaged bearing. The signal obtained using the MEMS accelerometer was sent to MATLAB to perform a signal processing task. The algorithm used for the signal processing method is shown in Fig. 1:

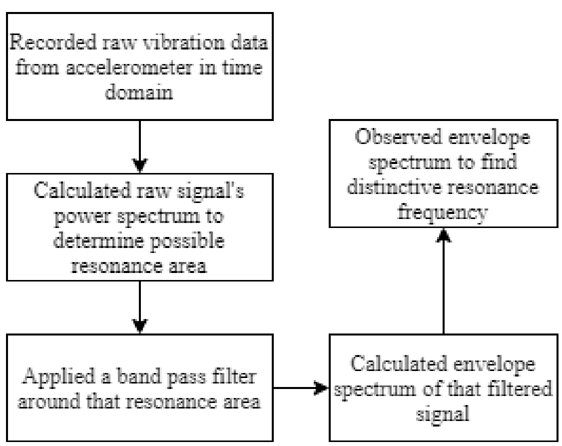

Fig. 1 Flow chart of signal processing using High Frequency Resonance Technique (HFRT)

The fault in the ball bearing generates an amplitude modulated impulse signal. In the first step of analysis, the raw vibration data along three axes were acquired in the time domain using ADXL345 MEMS accelerometer. The sensor was set to record the data at a sampling rate of 3200 Hz. The data was sent to the computer using RS-232 communication for further processing in MATLAB. However, due to the speed limit of library functions used in Arduino and MATLAB, the data was transmitted at a sampling rate of around 350 Hz only as a higher sampling rate causes the data to be clipped. This reduction in sampling rate, however, did not affect the sampling rate of the sensor, it occurred only during the data transmission between Arduino and MATLAB.

In the second step, the power spectrum of the signal was calculated to find the resonance area. After that, a bandpass filter around that resonance frequency was applied to enhance the fault induced signal. The bandwidth was chosen ±200 Hz around the resonance frequency determined by visual inspection at the power spectrum. Then the envelope spectrum of the signal was calculated to find bearing fault characteristics frequency.

3. Experimental rig

The experiment was done on bearing model SKF 6203. They are single row deep groove ball bearings having eight balls and made of stainless steel. They are commonly used, low-cost, and convenient for testing. The notable specifications of test ball bearing are available in [13]. A CAD design of the bearing is illustrated in Fig.2.

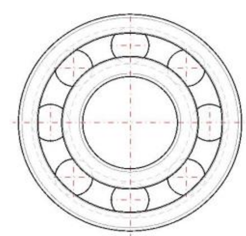

Fig.2 CAD design of SKF 6203 ball bearing. © Copyright. SKF®

The experimental set up as shown in Fig. 3 was comprised of two subsystems: an assembly of all mechanical components and a data acquisition system.

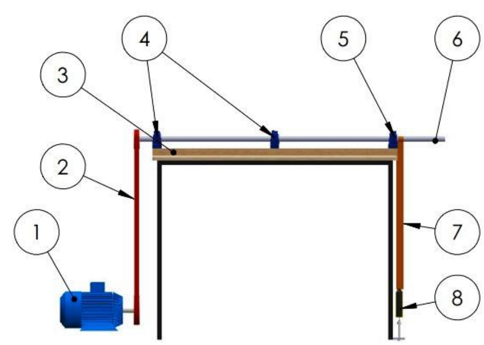

Fig.3 Experimental setup: (1) ½ HP motor (2) V belt (3) Wooden platform (4) Support bearing, B_2 and B_3 (5) Test bearing, B_1 (6) shaft (7) String (8) spring gauge

A single-phase induction motor was fixed to the floor with royal bolts. The power was transmitted to the shaft using a belt pulley system to dampen the vibration of the motor. On the other side of the shaft, a spring gauge was attached to apply load. The shaft was supported by three equal distanced bearings. The setup was carefully designed so that unnecessary vibration can be avoided. So every fastener was installed with rubber pads to provide vibration isolation and damping.

The data acquisition system with analyzing unit consists of a low-cost MEMS ADXL 345 accelerometer and an Arduino UNO. This sensor was selected due to its inbuilt analog to digital converter and high frequency response. The remarkable features of this MEMS based accelerometer can be found in [14].
For getting better results the accelerometer was mounted just on the top of bearing housing using a thin layer of cyanoacrylate adhesive as shown in Fig.4. Cyanoacrylate is recommended by sensor manufacturers for accelerometer mounting as it creates a stiff bond and thus the vibration of bearing is duly transmitted to the sensor [15]. Also due to the thin layer applied, it can sense the vibration accurately [16].

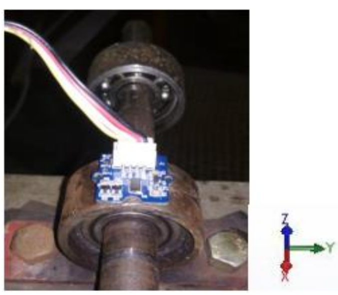

Fig.4 ADXL 345 mounting

After preparing the setup, a compatible Arduino program was uploaded for data acquisition purposes. The sensor sent data to the microcontroller using SPI serial communication. The microcontroller was connected to the COM port of the computer which was accessed using a MATLAB program. After receiving the data in MATLAB, signal processing using High Frequency Resonance Technique was applied. The signal processing task was programmed to record 10,000 data points from accelerometer over a period from which the sampling rate was calculated.

4. Experimental Results and Discussions

4.1 Experimental Parameters

The experimental condition under which data acquisition was performed is given in Table 1.

Table 1 Experimental Parameters

Sensor Sampling Rate	3200
Shaft rpm	2400
Load	0 kg
Number of Samples	10000

4.2 Acquisition of time domain signal

The first step is the acquisition of raw vibration signals in the time domain. Two signals were obtained for a damaged and healthy bearing. The signal is presented in Fig.5

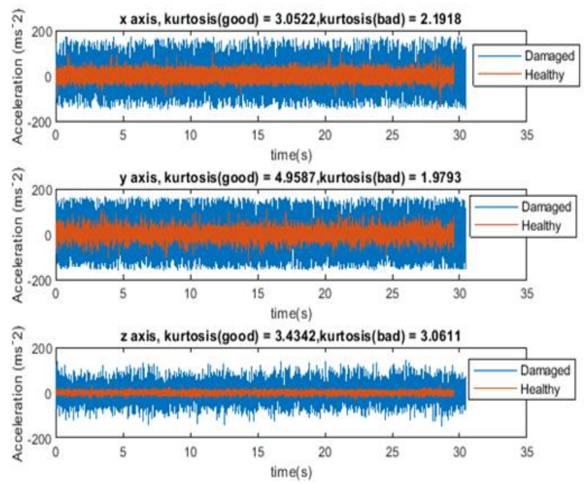

Fig.5 Time domain vibration signal

From the raw vibration signal along three-axis, it is clear that the assumed damaged bearing causes a significantly high amplitude of vibration. This is a primary indication of the presence of the fault.

4.3 Power Spectral Density Calculation

The power spectral density of the raw vibration signal is calculated to find the resonance of the bearing structure. The spectrum is shown in Fig.6

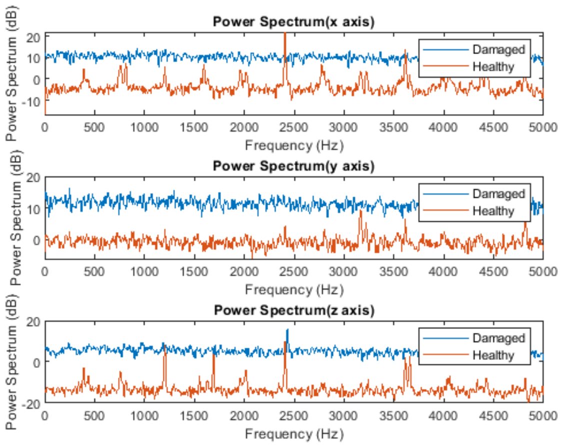

Fig.6 Power spectrum of raw vibration signal

The power spectral density shows high energy levels in the damaged bearing. There is also a high energy spike seen at around 2500 Hz. This spike might be caused due to the resonance of the structure. From this analysis further evidence is obtained that one of the bearings is damaged.

4.4 Bandpass filtering

A bandpass filter is applied to the raw vibration signal. The bandpass filter bandwidth is selected 2500±200 Hz. Thus, the fault characteristic frequency is enhanced and other noises that do not contribute to bearing resonance are subdued. The signal before and after bandpass filtering is shown in Fig.7

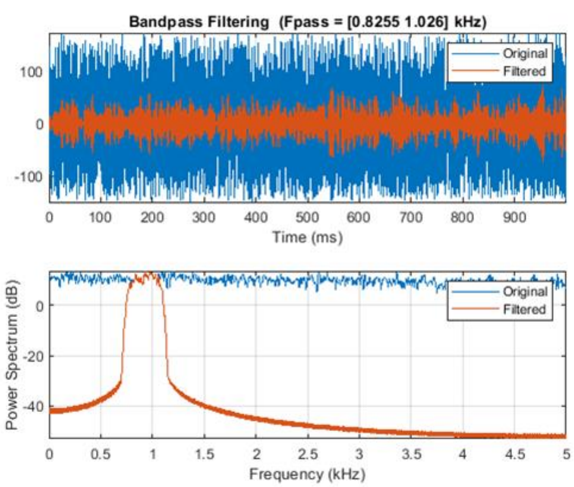

Fig.7 Bandpass filtering around resonance frequency

4.5 Envelope Analysis

As the bearing vibration with defect is amplitude modulated, the frequency contents of the envelope signal will show defect frequency. So, the envelope signal of both bearings was obtained from the bandpass filtered raw vibration signal.

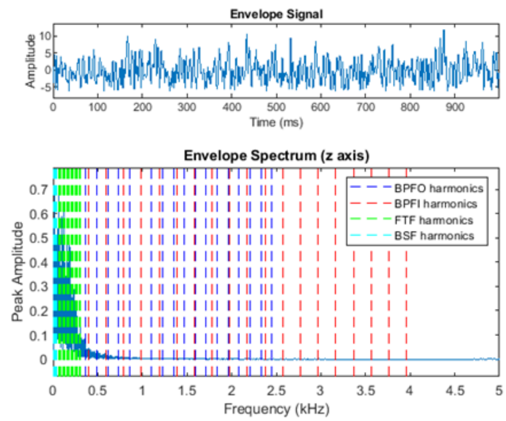

Fig.8 Envelope spectrum of filtered signal

From the envelope spectrum, we see that the frequency domain signal is mostly dominated by characteristic frequencies and its harmonics. Harmonics of all types of fault characteristic frequencies can be seen in the envelope spectrum shown in Fig.8. So, we can conclude that the bearing is severely damaged and all types of fault are present.

5. Conclusion

In this cost-effective method of bearing vibration analysis, authors combined the use of MEMS accelerometer for data acquisition and the HFRT process for data analysis. It was found that the method is successful in detecting bearing fault and its location. This is a useful information that the low cost ADXL-345 based vibration monitoring system can be used instead of costly industrial sensors. However further studies are needed to analyze the effect of load change, shaft misalignment, lubrication etc. The experiment was done on a pair of bearings which is low in terms of sample size. More studies are needed before this method is installed in industries. As in industrial application it is more important to detect bearing damage early, we have found that the tool and methodology used in this experiment can be used to detect bearing fault at the early stage of bearing life. The sensor can be easily mounted to any rotating machinery and the method prescribed would be able to detect its bearing condition. Also as the method uses real-time data transmission between microcontroller and the signal processor, this paves the way to low cost on-line vibration monitoring as well.

6. Acknowledgment

This work was fully funded by the Department of Mechanical Engineering of Bangladesh University of Engineering and Technology. The authors are thankful to the department. Also they would like to express humble gratitude to the Instrumentation and Solid Mechanics laboratory assistants of this department.

References:

[1] Orhan, S., Aktürk, N., & Celik, V. (2006). Vibration monitoring for defect diagnosis of rolling element bearings as a predictive maintenance tool: Comprehensive case studies. Ndt & E International, 39(4), 293-298.

[2] Patel, V. N., Tandon, N., & Pandey, R. K. (2010). A dynamic model for vibration studies of deep groove ball bearings considering single and multiple defects in races. Journal of Tribology, 132(4).

[3] McFadden, P. D., & Smith, J. D. (1984). Vibration monitoring of rolling element bearings by the high-frequency resonance technique—a review. Tribology international, 17(1), 3-10.

[4] Randall, R. B., & Antoni, J. (2011). Rolling element bearing diagnostics—A tutorial. Mechanical systems and signal processing, 25(2), 485-520.

[5] Sawalhi, N., Randall, R. B., & Endo, H. (2007). The enhancement of fault detection and diagnosis in rolling element bearings using minimum entropy deconvolution combined with spectral kurtosis. Mechanical Systems and Signal Processing, 21(6), 2616-2633.

[6] Darlow, M. S., Badgley, R. H., & Hogg, G. W. (1974). Application of high-frequency resonance techniques for bearing diagnostics in helicopter gearboxes (No. MTI-74TR25). Mechanical Technology Inc Latham NY.

[7] McFadden, P. D., & Smith, J. D. (1984). Vibration monitoring of rolling element bearings by the high-frequency resonance technique—a review. Tribology international, 17(1), 3-10.

[8] Howard, I. (1994). A Review of Rolling Element Bearing Vibration 'Detection, Diagnosis and Prognosis' (No. DSTO-RR-0013). Defence Science And Technology Organization Canberra (Australia).

[9] P. D. McFadden and J. D. Smith, Model for the vibration produced by a single point defect in a rolling element bearing, *Sound and Vibration*, vol. 96, pp. 69-82, 1984.

[10] Chaudhury, S. B., Sengupta, M., & Mukherjee, K. (2014). Vibration monitoring of rotating machines using MEMS accelerometer. International journal of scientific engineering and research, 2(9), 11.

[11] Maruthi, G. S., & Vittal, K. P. (2005, November). Electrical fault detection in three phase squirrel cage induction motor by vibration analysis using MEMS accelerometer. In 2005 International Conference on Power Electronics and Drives Systems (Vol. 2, pp. 838-843). IEEE.

[12] Saruhan, H., Saridemir, S., Qicek, A., & Uygur, I. (2014). Vibration analysis of rolling element bearings defects. Journal of applied research and technology, 12(3), 384-395.

[13] 6203|SKF. (n.d.). Retrieved October 26, 2020, from https://www.skf.com/group/products/rolling-bearings/ball-bearings/deep-groove-ball-bearings/productid-6203

[14] Analog Device.inc, "ADXL 345." ANALOG DEVICES, pp. 1–40, 2015.

[15] Guidelines for adhesive mounting accelerometers. Retrieved October 26, 2020, from https://www.te.com/content/dam/te-com/documents/sensors/global/guidelines-adhesive-mounting-accelerometers-app-note.pdf

[16] Hanly, S. (n.d.). Accelerometer Mounting Best Practices for Vibration Measurement. Retrieved October 28, 2020, from https://blog.endaq.com/accelerometer-mounting-best-practices-for-vibration-measurement