Health State Indicator-Based Vibration Signature for Gearbox Condition Monitoring and Maintenance

by Ismoyo Haryanto

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Health State Indicator-Based Vibration Signature for Gearbox Condition Monitoring and Maintenance

A Widodo[1], Dj Satrijo[1], T Prahasto[1] and I Haryanto[1]

[1]Department of Mechanical Engineering, Faculty of Engineering, Diponegoro University, Jl. Prof. Soedarto, Tembalang Semarang 50275 Indonesia

*awid@undip.ac.id

Abstract. Gearbox is a device used to transmit the power of rotating machinery from the prime mover to the equipment with or without change in rotational speed. The working condition of gearbox is usually experienced in heavy load, suffering high friction when contacted with pinion and running in high speed rotation. Therefore, the condition of gearbox must be reliable to ensure the functional operation. The present study deals with development of health state indicator derived from vibration signature for gearbox condition monitoring and maintenance. Vibration technique is still the best way to machine condition monitoring including gearbox. However, wear detection of gearbox is still under study due to the difficulties of capturing best signature of wear by means of vibration signal. In this study, health state indicator is proposed based on vibration signature to monitor wear progress in gearbox thru averaged and moving-averaged logarithmic ratio from filtered vibration signal. The results show that averaged logarithmic ratio is increased as well as the increasing of wear based on experimental work. Moving-averaged logarithmic ratio is also investigated in present work and both method has potential to be indicators for wear monitoring and detection.

1. Introduction

Gear is one of machine elements that is vital for mechanical power transmission and widely used in rotating machinery for reduction or increasing the speed of shaft. Gearbox has been applied to mechanical power transmission since long time ago and is very popular technique due to the effectiveness, reliable and can serve a very high power transmission. However, gearbox often suffers deterioration in performance due to heavy duty task when transmitting power especially faults caused by wear. Wear is a kind of fault that frequently occurs in the gearbox. It refers to progressive material removal from contacting surfaces due to combination of carrying heavy load, sliding and rolling motions under mixed or boundary lubrication conditions. Wear in a gearbox will produce error of dynamics transmission, power losses during transmission, high vibration level and noise [1][2]. Severe conditions of wear leads to catastrophic failure of gearbox, i.e., one or more broken teeth. Therefore, the topic of gear wear monitoring is receiving considerable attention in research of machine condition monitoring.

The effects of wear in gearbox towards dynamic features has been theoretically investigated by several researchers. Tooth surface wear gives significant effects on the dynamic load and its distribution. It causes some changes in tooth working surface that leads to gear transmission ratio would no longer be static, especially in spur gears where transmission error are highly sensitive to wear [2][3]. Other researcher reported that dynamic features could also effect wear mechanism, so actually there is two-ways impact relations between them [4]. Therefore, it is possible to develop a technique of gearbox monitoring based on the changes of dynamic features due to wear.

Study of gearbox vibration due to wear is relatively sparse due to the complexity of vibration signals generated from gearbox under wear condition. The past research have revealed that uniform tooth wear will increase the amplitude of gear mesh harmonic frequency, and the amplitude of higher order frequency are the best way of detecting uniform wear in gearbox at early stage [5][6]. Other paper reported the use of cepstrum and spectrum analysis to identify the wear state for high contact ratio gear pairs. This research reported that the faults such as scuffing and pitting was successfully detected by rahmonic and harmonic features [7][8]. The present work also intends to confirm the work of [9] but the data of gearbox were contained normal and slightly wear.

2. Method and Material

2.1. Time-synchronous averaging (TSA)
TSA is a method of signal processing which extracts periodic waveform signals from noisy data. TSA is regarded as a suitable method for extracting information from gearbox due to its ability to separate the original signal come from gearbox from other signal resources. Equation (1) presents TSA of gearbox signal modeled by mathematical expression that consists of summation of amplitude-modulated and frequency-modulated signals.

$$x(t) = \sum_{k=1}^{K} X_k [1 + a_k(t)] \cos[2\pi k N_g f_1 + \phi_k + b_k(t)] \quad (1)$$

where X_k is the *k-th* of amplitude of gear mesh (GMF), f_1 is gear mesh frequency (GMF), N_g is the number of teeth, ϕ_k is initial phase, $a_k(t)$ is amplitude-modulated function and is $b_k(t)$ phase-modulated function [4].

2.2. Root-means square (RMS)
RMS is the square root of the averaged of the squared values of amplitude waveform. RMS measure is an important parameter of the amplitude of vibration signal. It measures the energy and power content in the vibration signal. To obtain this values, the amplitude of waveform must be squared and then the squared values averaged over a certain length of time. The minimum interval time is one periode of the waveform. RMS of vibration signal is calculated by equation 2.

$$RMS = \sqrt{\frac{\sum_{i=1}^{N} X_i^2}{N}} \quad (2)$$

where X_i is input data of signal and N is the number of data.

2.3. Side band ratio (SBR)
SBR is defined as ratio of squared RMS and squared amplitude of the vibration data. SBR is obtained from the first two meshing harmonic frequencies, but it may not sufficient for wear detection due to representing only part of gear tranmission feature. However, the SBR which is obtained from a number of harmonic meshing frequencies could be available in wear detection due to putting together of all information of tranmission features contained in the signals. SBR can be regarded as state vector and is formulated as follows [9].

$$\mathbf{SBR}_i = \frac{[RMS_i]^2}{X_i^2} \quad (3)$$

where RMS_i is the root-means square (RMS) and i = 1,2,3, ... is the number of harmonics.

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2.4. Averaged and moving-averaged logarithmic ratio

Tooth wear will cause increasing deviation in the working surface area of gearbox. It starts from initial state and will change the mating character especially tooth-to-tooth difference. Therefore, the state vector $\mathbf{SBR}_i$ will also change accordingly. If we assume $\mathbf{SBR}_0$ is initial state vector and during operation this vector will change to $\mathbf{SBR}_i$, it means some differences emerge between $\mathbf{SBR}_i$ and $\mathbf{SBR}_0$ due to operation conditions. The change of such difference actually represents change of gear state due to wear tooth and can be expressed as averaged logarithmic ratio [9].

$$ALR_{i,0} = \frac{1}{K}\sum_{k=1}^{K}\left|\ln\frac{SBR_{i,k}}{SBR_{0,k}}\right| \tag{4}$$

Another method for wear tooth detection uses moving reference of a time varying that called moving-averaged logarithmic ratio. This indicator is addressed to assess the trend of wear tooth in the gearbox and formulated as follows

$$mALR_i = \frac{1}{K}\sum_{k=1}^{K}\left|\ln\frac{SBR_{i,k}}{SBR_{i-1,k}}\right| \tag{5}$$

where k is the order of meshing harmonic as presented in equation 1.

2.5. Data Experiment

Data experiment used in this research were originated from the GOTIX Project housed by GIPSA-Lab. This project aims to characterize the defect of mechanical system such as gearbox. The experiment had been conducted in long term measurement for wear tooth study. GOTIX Project was equipped by gearbox test bench that consists of electrical motor: three-phase, asynchronous, 55 kW and gear train enclosed in the gearbox of 57/15 multiplier, with parallel straight teeth either in cased hardened or in semi-hardened. The load of the test bench was a DC generator of 54 kW commanded by *leroy-somer* DMV 2342 inverter. Power supply used in the test bench was AC power of 340 V, 50 Hz.

Vibration data acquisition was conducted by 8 accelerometers and speed rotation of 750 rpm was measured by tachometer. Sampling frequency used was 25 kHz and the time length for data acquisition was 80 seconds. Figure 1 shows the accelerometers installed in the gearbox for vibration measurement.

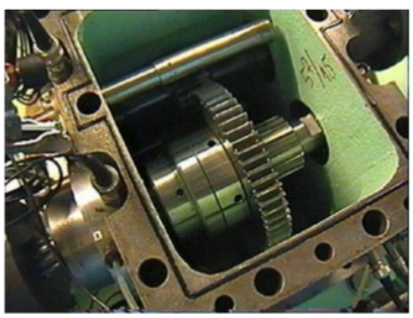

Figure 1. Accelerometers for vibration measurement of the gearbox

3. Result and Discussion

Vibration measurement of gearbox and tachometer measurement of rotating speed produce signals in time domain as presented in Figure 2. The measured signals are very complicated in information contained due to acquired in high frequency sampling. Many information related to condition operation and environment noise are possibly not deliberated contained or even interfere the acquired signals, so that the desired signals which is originated purely from the gearbox are then buried by noise and

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unwanted signals. Therefore, the such signals are need to be analyzed for extracting the valuable information related to the machine condition.

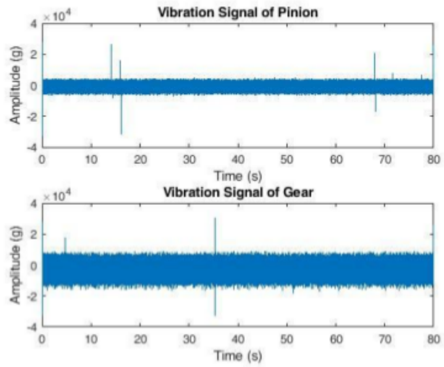

Figure 2. Vibration and tachometer signals of tested gearbox

The use of TSA in analyzing vibration signals is addressed to separate the originated signals from gearbox and other unwanted signals. Noise buried in the signals usually make the signals are distorted so that the real information that is needed for defect detection gives inaccurate result or even false. Presentation of vibration signals after employing TSA is shown in Figure 3. After TSA, vibration signals is significantly reduced both in amplitudes and frequency. This means that the unwanted signals has been successfully removed from the origin signals. The further analysis after TSA is expected to be success since unwanted signals have not interfered anymore.

However, the signals resulted from TSA are still confusing when they are used for wear tooth detection. Figure 4 shows the faulty signal comes from gearbox which was experienced by wear but the difference between health and faulty signal could not be easily distinguished. There is only slight difference in amplitudes between healthy signal and faulty signal. The waveform in Figure 4 tends to be similar even though the wear tooth has already been introduced. Some difficulties will emerge when original time domain signals used for fault detection because the information contained in signals still buried due to high number of data acquired in high frequency sampling. Therefore, feature extraction is needed thru, i.e., using statistical analysis for random signals [10].

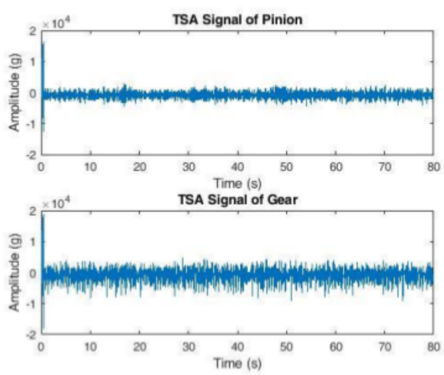

Figure 3. Vibration signals of pinion and gear after TSA in normal condition (health)

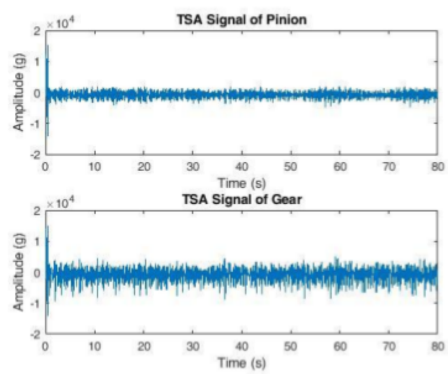

Figure 4. Vibration signals of pinion and gear after TSA in fault condition

Another method is presented namely fast-fourier transform (FFT) analysis for wear tooth detection as shown in Figures 5 and 6. Both figures seems similar in presenting peaks of specific frequencies for pinion and gear. Usually, machine fault detection and diagnosis are performed based on specific fault frequencies resulted from vibration signals. Frequency analysis is the best tool for finding specific faults in machines. However, FFT analysis could not represent significant different of peaks in specific frequencies of gearbox when experienced by wear tooth. It means that FFT analysis difficult to capture specific wear tooth frequencies and could be indicator of wear in gearbox.

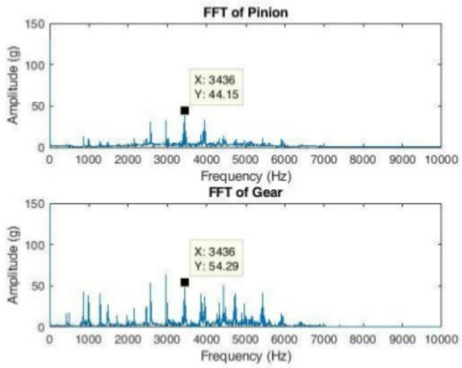

Figure 5. FFT of vibration signals in normal condition (health)

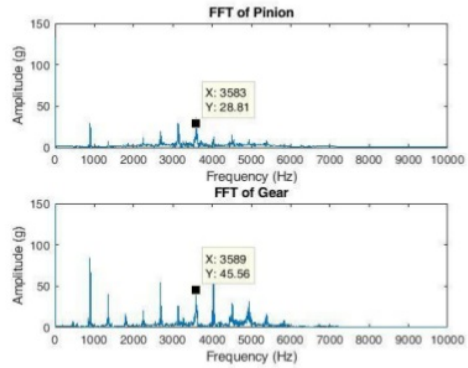

Figure 6. FFT of vibration signals in fault condition

Further analysis of wear tooth detection was also performed by spectrogram analysis. Basically, spectrogram is visual representation of the spectrum of frequencies of vibration signals as it varies with the time. Spectrogram is capable to highlight the events contained in the vibration signals which is specially happened in a short time duration. Moreover, spectrogram also gives information related to the energy of the signal in a specific time of event. In this study, spectrogram is aimed to capture wear tooth progress of the gearbox which is indicated by power density during acquisition time. Spectrogram of vibration signals of the gearbox is depicted in Figure 7 and 8. The result of spectrogram detection is similar to the previous method that is difficult to recognize the wear tooth in the gearbox.

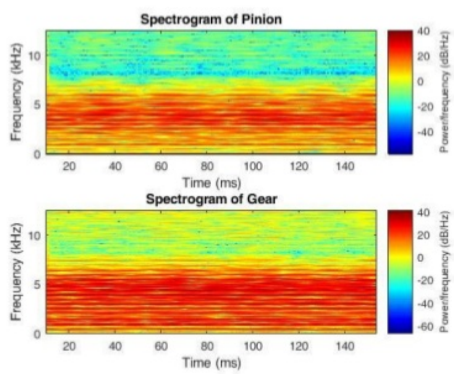

Figure 7. Spectrogram of vibration signals in normal condition (health)

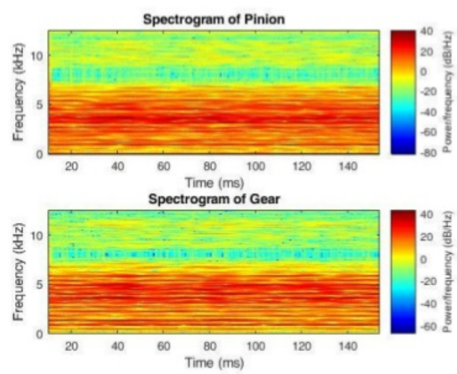

Figure 8. Spectrogram of vibration signals in fault condition

Figure 9 and 10 show trend of averaged and moving-averaged logarithmic ratio of vibration signals during data acquisition. The trend of both feature shows the increasing values of averaged and moving averaged ratio as increasing the experiment number. Progressive of wear tooth is successfully captured by such features. Even though, both feature is decreased for 5*th* experiment of pinion signal, but next experiment shows increased values until end of experiment. Vibration data of gear shows better performance of trending, especially after 4*th* experiment. The trending is consistently increased from 4*th* experiment till the end of experiment. Actually, this trending represents that averaged and moving-averaged logarithmic ratio are potential to be indicator of wear in the gearbox based on vibration signals. This results is good agree with the investigation of wear tooth detection performed by [9].

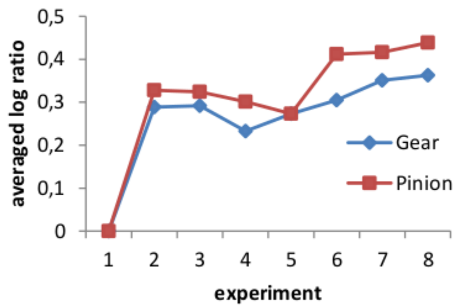

Figure 9. Trend of the averaged logarithmic ratio of vibration signals

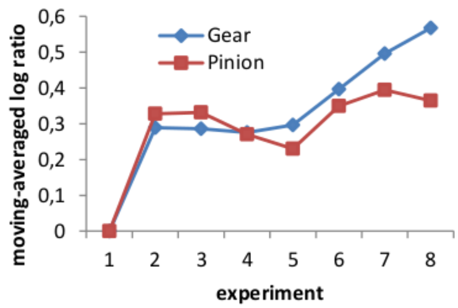

Figure 10. Trend of the moving-averaged logarithmic ratio of vibration signals

4. Conclusion

This paper deals with a development of health state indicator of gearbox using vibration signals. The present study is aimed to propose a method for wear tooth detection base on filtered vibration signal by means of TSA. After TSA, statistical feature namely RMS was calculated to produce series of vectors called side band ratio (SBR). Averaged and moving-averaged logarithmic ratios are then calculated from SBR vectors from which the health state indicators are derived. Observing such indicators, progressive trends have been resulted that show the progress of wear tooth in gearbox based on experiment data. Comparing with other methods such as FFT and spectrogram, averaged and moving-averaged logarithmic ratio give better results in detection of wear tooth than the previous methods. This means the proposed method is promising to be indicators of wear in the gearbox and can contribute in gearbox condition monitoring and maintenance.

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