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Submission date: 08-May-2020 11:50AM (UTC+0700)

Submission ID: 1319159599

File name: widodo2017.pdf (1.82M)

Word count: 2397

Character count: 12726

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Citation: AIP Conference Proceedings **1831**, 020053 (2017); doi: 10.1063/1.4981194
View online: http://dx.doi.org/10.1063/1.4981194
View Table of Contents: http://aip.scitation.org/toc/apc/1831/1
Published by the American Institute of Physics

Fault Detection of Gearbox Using Time-Frequency Method

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Abstract. This research deals with fault detection and diagnosis of gearbox by using vibration signature. In this work, fault detection and diagnosis are approached by employing time-frequency method, and then the results are compared with cepstrum analysis. Experimental work has been conducted for data acquisition of vibration signal thru self-designed gearbox test rig. This test-rig is able to demonstrate normal and faulty gearbox i.e., wears and tooth breakage. Three accelerometers were used for vibration signal acquisition from gearbox, and optical tachometer was used for shaft rotation speed measurement. The results show that frequency domain analysis using fast-fourier transform was less sensitive to wears and tooth breakage condition. However, the method of short-time fourier transform was able to monitor the faults in gearbox. Wavelet Transform (WT) method also showed good performance in gearbox fault detection using vibration signal after employing time synchronous averaging (TSA).

INTRODUCTION

The most popular method for condition monitoring and fault diagnosis of gearbox is using vibration signal. Such signal is usually acquired by accelerometers that are installed on gearbox housing. The purpose of fault diagnosis in gearbox is to detect the existing faults and to determine the source of faults in early stage condition. Another target of fault diagnosis is also to detect the impending faults in the gearbox when they are operating. In gearbox vibration analysis, the main component of vibration signal of gearbox is gear mesh frequency (GMF) and its harmonics. The sidebands of GMF inform the actual conditions of gearbox. The number of sidebands and the magnitude of its amplitudes can indicate the severity of faults and its sources (Randall, 1982).

Cepstral analysis was usually used for condition monitoring of gearbox. This method was suitable for sidebands detection of vibration spectra, and it can be a feature that represents gearbox condition. Since the cepstrum estimates the average sidebands spacing over a wide frequency range, it allows accurate measurement of sidebands periodicity. So therefore, it was applicable for both detection and diagnosis of gear faults (Randall, 1987).

In study of gearbox fault detection, signal separation method was reported by Elasha et al. (2016). Signal separation was conducted on vibration signal based on time domain due to the presence of interfered signal from bearings. The techniques of least mean square (LMS), self-adaptive noise cancellation (SANC) and fast block LMS were used in the purposed method. The results show a clear separation signal of gearbox and bearings so that the fault detection can be easily performed.

In addition, the used of time domain vibration signals for gearbox detection and diagnosis was reported by Hong et al. (2014). He proposed a method to improve the capability of fetaure extraction for gear monitoring and diagnosis. Continuous monitoring of gearbox thru vibration signal detects the deterioration due to propagation of faults which tells the defect in gear, in order to schedule the proper maintenance to avoid unexpected shutdown cost and time (Mohammed et al., 2013).

7th International Conference on Mechanical and Manufacturing Engineering
AIP Conf. Proc. 1831, 020053-1–020053-8; doi: 10.1063/1.4981194
Published by AIP Publishing. 978-0-7354-1499-0/$30.00

Another spectral analysis was called spectral correlation density (SCD) of vibration signal to seek the correlation between meshing harmonics and their sidebands. SCD was considered as characteristic of primary spectrum that affected by gear faults. Therefore, SCD function was able to identify the gear faults (Rubini et al., 1997).

Gear faults will produce impact when rotate in operating conditions such as carrying load, start up or coast down. This phenomena produce excitation that can be considered as transient vibration signal. In such case, the vibration signal can be classified as non-stationary signal. However, most of widely used signal processing techniques work based on an assumption of stationary and globally characterize signal. Therefore, this technique is not suitable for detecting short-duration dynamic phenomenon, as a fact that time localization of transient events is very difficult. On the other hand, the approach of time-frequency distribution such as wavelet transform is suitable (Staszewski et al., 1994; McFadden, 1994; Seo et al., 2014). By means of this time-variant procedure it is possible to detect and localize the presence of faults in gearbox.

In this paper, the above-mentioned method are employed to experimental vibration data that concerns a gear pair affected by wear and tooth breakage of one of the teeth. The capability of the proposed method is evaluated in detecting and diagnosing the presence of the faults in the gears. The performance of each method will be compared to obtain the most effective method based on experimental works.

EXPERIMENTAL WORK

Data acquisition of vibration signal was conducted on back-to-back gear test rig through three accelerometers. Three gears were tested including normal, wear and broken teeth gears for generating vibration signal. At first, the test rig was loaded by employing twist moment to the input shaft while the output shaft was locked. One teeth overlap of gears pair was set to ensure the load of twist moment and the input shaft was rotated at 1000 RPM. In the data acquisition process, the sampling rate was 5 kHz, maximum frequency range was 6 kHz and the data number was 40960 data. Optical sensor was also employed to acquire the signal of shaft rotation for TSA purpose. The experimental work is presented in Fig. 1.

FIGURE 1. Data acquisition process of vibration signal

MATHEMATICAL MODEL

Time Synchronous Averaging

TSA is one of signal processing techniques that is able to extract the periodicals component of signals from the noisy signals. The use of TSA is suitable for analysis of gears vibration signals due to its capability to separate gear vibration signal from other asynchronous signals. TSA is formulated as follows (McFadden, 1987):

$$y_{av}(t) = \frac{1}{N}\sum_{n=0}^{N-1} y(t+nT) \tag{1}$$

Where *N* is rotating speed (RPM), *n* refers to sampling data number and *T* is period.

Short-Time Fourier Transform (STFT)

STFT method is also called the windowed fourier transform, partitions the time domain input signal into several overlapped blocks by multiplying the signal with window function, then applies the DFT to each block. In this case, window functions also called sliding windows, are function which the amplitude tapers gradually and smoothly toward zero at the edges. Eq. (2) presents the formulation of STFT (Allen, 1977) Allen:

$$x(\tau,\omega) = \int_{-\infty}^{\infty} x(t)\omega(t-\tau)e^{-j\omega t}\,dt \tag{2}$$

Where ω is window function, and *x*(*t*) is the signals to be transformed.

Wavelet Transform (WT)

Wavelet may be seen as a complement to classical Fourier decomposition method. A wavelet means a small wave that decays quickly. Morlet (1982) considered wavelet as a family functions constructed from translations and dilatations of single function called 'mother wavelet' (Chui, 1992). The projection of a function x onto subspace of scale a then has the form:

$$x_{a,b}(t) = \int_{-\infty}^{\infty} \psi\left(\frac{t-b}{a}\right)x(t)dt \tag{3}$$

Where a and b are scale factor and parameter of translation, respectively. The function ψ is continuous function and can be expressed as:

$$\psi_{j,k}(x) = 2^{\frac{j}{2}}\psi(2^{j}x-k)\ ;\ j,k \in Z \tag{4}$$

RESULTS AND DISCUSSION

STFT of vibration signal acquired from normal gear is presented in Fig. 2. Vibration amplitude is depicted by color palette that represents the levels of amplitude from higher level (red color) to lower level (light blue). The STFT of normal gear produces a tidy degradation of color palette and it does not show a scattered distribution of color palette that indicates faults in gear. In the case of wear condition, vibration signal shows higher amplitudes and are spread evenly along frequency range of data acquisition. The red color dominates the region of frequency range both low and high frequency range. The presentation of STFT produced by the wear gear is shown in Fig. 3.

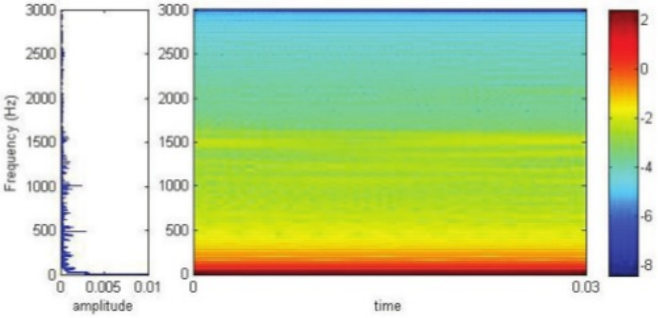

FIGURE 2. STFT of normal gear

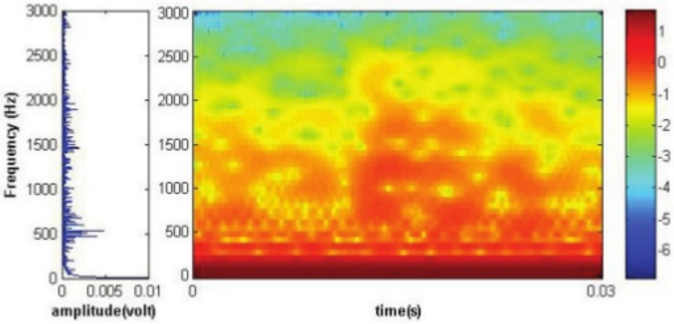

FIGURE 3. STFT of gear in wear condition

The tooth breakage produces vibration signal that consists of many impulses during its rotation. High amplitude emerges significantly at the low frequency range, that is around 500 Hz and its harmonics. Distribution of high amplitude in the STFT is not spread evenly. Fig. 4 shows the distribution of red color (high amplitude) exist only at the specific range, mainly on the low frequency region. While, the lower amplitudes are spread out at the high frequency region. This phenomenon is shown by light blue color in the STFT of Fig. 4.

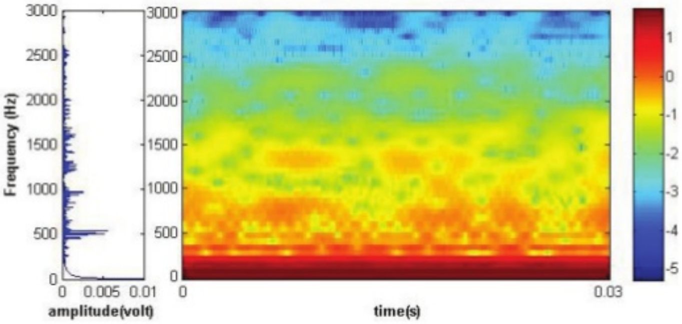

FIGURE 4. STFT of gear in tooth breakage condition

TSA analysis of normal gear shows that the pattern in tidy condition. Amplitudes of the signal of normal gear are relatively same at all rotation angles as presented in Fig. 5. Wear gear gives relatively same vibration signal patterns along the rotation angle including the amplitudes of vibration. Fig. 6 shows the starting of the wear is beginning on position of shaft angle 160° measured from reference. The increasing of the vibration frequency of the shaft angle from 160° to 300° indicates the problem of wear takes effect the vibration signals.

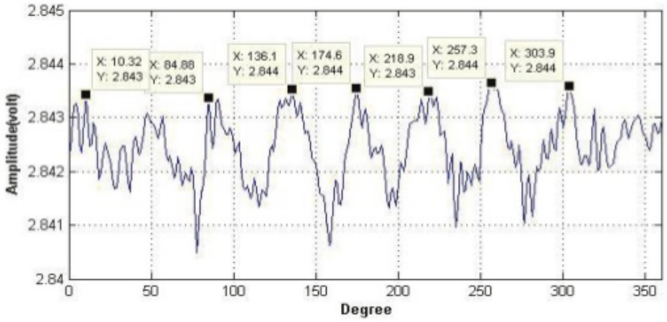

FIGURE 5. TSA of vibration signal of normal gear

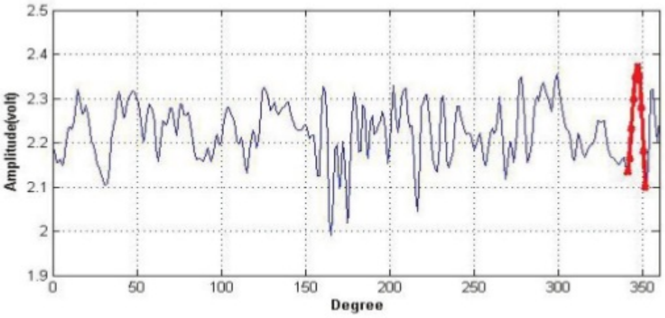

FIGURE 6. TSA of vibration signal of wear gear

The tested gear with single tooth breakage gives different TSA patterns along rotation of shaft angle. Fig. 7 shows the tooth breakage location is around shaft angle of 20°. The increasing of frequency and amplitudes of TSA pattern around angle 20° can identify the location of tooth breakage.

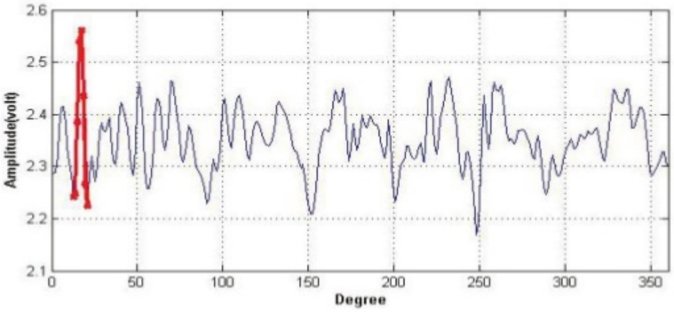

FIGURE 7. TSA of vibration signal of single tooth breakage.

Wavelet analysis of vibration signals acquired from gears in normal, wear and single tooth breakage conditions are presented in Figs. 8-10. Continuous wavelet transform (CWT) of vibration signal of the gear in normal condition shows the wavelet coefficients are relatively uniform (Fig. 8). CWT of vibration signals from wear gear produces the distribution of wavelet coefficient is uneven, mainly for the location of shaft angle 160° (Fig. 9). This phenomenon is also happened for single tooth breakage condition where the CWT of its vibration signals gives the distribution of wavelet coefficient varies and gives different patterns (Fig. 10).

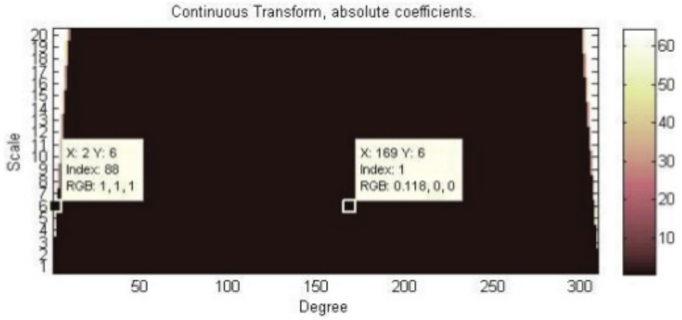

FIGURE 8. CWT coefficient of vibration signal of normal gear

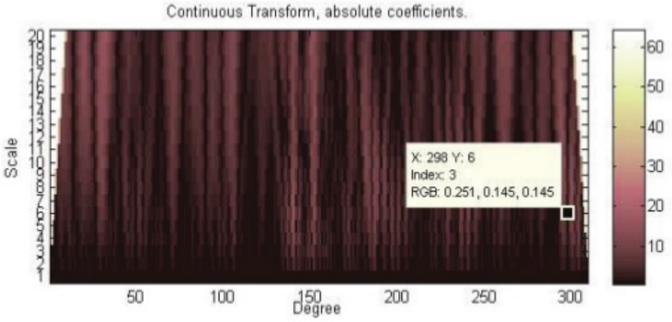

FIGURE 9. CWT coefficient of vibration signal of wear gear

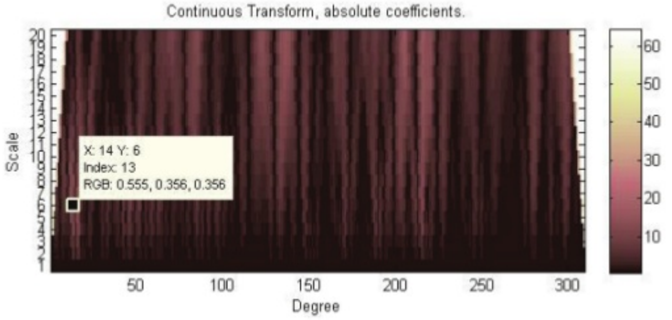

FIGURE 10. CWT coefficient of vibration signal of single tooth breakage gear

Observation of STFT, TSA and CWT methods for detection and diagnosis of gear faults show that the such methods has capability to detect faults in gear clearly based on frequency, amplitudes and fault location. In addition, the cepstrum analysis of wear gear is presented in Fig. 11 that shows the dominant peaks emerge clearly in the quefrency domain. The peaks refer to the faults in the gear, and the gear mesh frequency is also clearly presented.

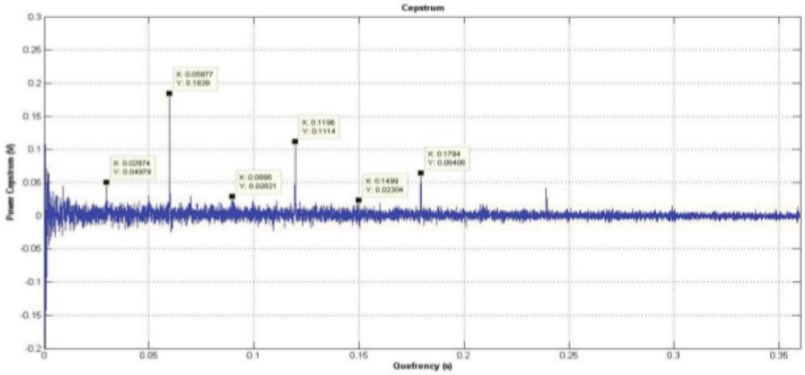

FIGURE 11. Cepstrum analysis of vibration signal of wear gear

CONCLUSION

This paper deals with the applications of STFT, TSA and CWT for detection and diagnosis of gear faults. STFT is able to show the distribution of vibration amplitudes toward its frequencies. However, the location of faults/defect in gear cannot be determined using STFT method. The use of TSA and CWT has capability to determine the relative location of faults based on angle of rotation of the shaft and frequency change when the rotation angle meets the faults. Cepstrum analysis is good for detection of faults in gear due to its capability to show the peaks that refers to the faults in specific quefrency domain. However, this method cannot determine the relative position of faults in gear.

ACKNOWLEDGEMENT

Authors thank to Ministry of Research, Technology and Higher Education of the Republic of Indonesia for supporting the research fund through the grant of *Penelitian Kompetensi* with Contract Number: 188-3/UN7.5.1/PG/2014.

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