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Gear fault detection using vibration analysis and continuous wavelet transform

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Abstract

Gears are the one of the most important machine components and widely used in transmission design of automobiles and other rotating machinery. In industry, breakdown of such crucial components causes heavy losses. This paper present two signal processing techniques used for the fault detection of a gear used in an internal combustion engine, they are conventional vibration spectrum analysis and continuous wavelet transform. A fault diagnosis engine test setup is built for experimental studies to acquire vibration signal from a healthy as well as simulated faulty gear. The vibration signals are acquired from internal combustion engine using accelerometer, under healthy and simulated faulty gear conditions. This paper represents application of the conventional vibration spectrum analysis and Morlet wavelet as a continuous wavelet transform used for the fault diagnosis of the gear.

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Keywords: Fault diagnosis,Fourier transformation,Continuous wavelet transform, Morlet wavelet;

1. Introduction

The gears are one of the major components in transmission systems of an automobile engine and proper maintenance of gear system is very essential to ensure performance of the engine. Vibration analysis is useful tool for machine health monitoring. Wavelet analysis is capable of detecting non-stationary, non-periodic, transient features of vibration signal efficiently. In this study, vibration and continuous wavelet transform (CWT) analysis is applied for gear diagnosis. Most of the defects in gear transmission assembly are being generated due to fatigue, wear, excessive loads, improper lubrication, backlash, eccentric teeth and occasionally manufacturing faults. These faults in gear may cause excessive vibration, noise, and even failure of transmission system.

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In an engine manufacturing industry, defects in gears may be arises during the assembly process in production line. Therefore, it is necessary to identify and eliminate the defective engines going into the market. Each component of engine equipment has a different signature in time and frequency spectrum.Time domain represents the dynamic responses depend on the interaction of many components of the system. In time versus frequency domain, wavelet transform (WT) facilitates multi-resolution analysis and hence, becomes popular to extract characteristics features of non-stationary vibrations signals.

Wavelet analysis are informative in scale (frequency)-time domain, compared with conventional vibration spectrum analysis which gives frequency domain information. (Peng et al. 2003). Tse et al. (2004) used exact wavelet analysis for machine fault diagnosis. Saravanan et al. (2010) examined the spur gear box fault detection using discrete wavelet for feature extraction and artificial neural network used as a classifier. Chandran et al. (2012) application of Laplace wavelet kurtosis used for fault diagnosis of gears. Al-Badour et al. (2011) time, frequency and wavelet analysis used study blade and shaft vibrations of turbo-machinery. Amarnath (2008) made an attempt experimentally with help of vibration and acoustic signalsfor fault detection of helical gear using Daubechie wavelet. Srikanth (2008) used conventional vibration analysis for the fault detection of two stroke internal combustion (IC) engines. The purpose of this paper is to extend the application of Fourier transform and continuous wavelets for fault diagnosis of gear used in internal combustion engine.

1.1 Fourier transform

Fourier transform (FT) is most widely used in vibration signal analysis. It simply converts given signal from time domain to frequency domain by integrating the given function over the entire time period. The integral Fourier transform for a non-periodic function *x(t)* is given by,

$$x(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} X(\omega)e^{i\omega t}\, d\omega \tag{1}$$

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

Where, $\omega$is fundamental frequency.Using these equations, a signal can be transformed into the frequency domain and back again. The FT is well suited to analyze stationary periodic functions-which will exactly repeat themselves once over period, without modification.Fourier transform is particularly used to convert a function from the continuous time to the continuous frequency domain, where as fast Fourier transform (FFT) is an efficient algorithm to compute the discrete Fourier transform and it's inverse. FT technique earned much of the importance in processing stationary signal. FFT is the one of the extension of it.

1.2 Wavelet Transform

The FT is not very useful for analyzing non-stationary signals since it fail to describe the frequency content of a signal at particular time. In signal processing, the limitation of FT led to the introduction of new Time-frequency analysis called Wavelet transform (WT). It is improved version of Fourier transform, can be used for analysing the components of a stationary signal.

Generally conventional data processing is computed in time or frequency domain. Wavelet processing combines both time and frequency. In simple language, we use term called 'time-frequency' analysis. A wavelet is a basis function characterized by, two aspects, one is its shape and amplitude, which is chosen by user. Second one is its scale (frequency) and time (location) relative to the signal.

The continuous wavelet transform can be used to generate spectrograms which show the frequency content of signals as a function of time. A continuous-time wavelet transform of x(t) is defined as:

$$CWT \quad X_{\Psi}(a,b) = \frac{1}{\sqrt{|a|}}\int_{-\infty}^{\infty} x(t)\, \Psi^{*}\left(\frac{t-b}{a}\right) dt, \ \ \{ a, b \in R, a \neq 0 \tag{3}$$

In above equation ψ (t) is a continuous function in time domain as well as the frequency domain called the mother wavelet and ψ* (t) indicates complex conjugate of the analysing wavelet ψ (t). The parameter 'a' is termed as scaling parameter and ‘b’ is the translation parameter. The transformed signal $X_\Psi(a,b)$ is a function of the translation parameter ‘b’ and the scale parameter ‘a’. In WT, signal energy is normalized by dividing the wavelet coefficients by $\frac{1}{\sqrt{|a|}}$ at each scale.

1.2.1 Morlet Wavelet

The Morlet wavelet transform is belongs to CWT family. It is one of the most popular wavelet used in practice and its mother wavelet is given by,

$$\Psi(t) = \frac{1}{\sqrt[4]{\pi}}\left(e^{jw_o t} - e^{-\frac{w_0^2}{2}}\right)e^{-\frac{t^2}{2}} \tag{4}$$

In above equation, w_0 refers to central frequency of the mother wavelet. The term $e^{-\frac{w_0^2}{2}}$ involved in above equation is specifically used for correcting the non-zero mean of the complex sinusoid, and in most of cases, it can be negligible when $w_0 > 5$. Therefore when the central frequency $w_0 > 5$, the mother wavelet redefined as follows;

$$\Psi(t) = \frac{1}{\sqrt[4]{\pi}}\, e^{jw_o t}e^{-\frac{t^2}{2}} \tag{5}$$

2. Experimental studies

The test rig setup was constructed to study fault detection of gear used in IC engine. The details about the experimental setup and experimental procedure are discussed in the following subsections.

2.1 Experimental setup description

The below figures shows the Line sketch and experimental engine test setup used for fault detection of gear used in internal combustion engine. The experiments were conducted on the Kawasaki Bajaj KB-100 two stroke spark ignition engine. In practice, the engine conditions are monitored at idle speed, which is nearer to 1000 rpm. Therefore the experiment has been carried out at constant rotational engine speed of 1080 rpm at 4^{th} gear position. Here the engine speed refers to the rotational speed of the crank. The engine was driven by using 3 Hp DC motor. The data has been acquired by using NI 9234 data acquisition (DAQ) card and analysed using Lab View 10.0 software from National Instruments (NI). Piezoelectric accelerometer with an operating frequency range between 1 to 5000 Hz was used to pick up vibration signals from the gear box casing.

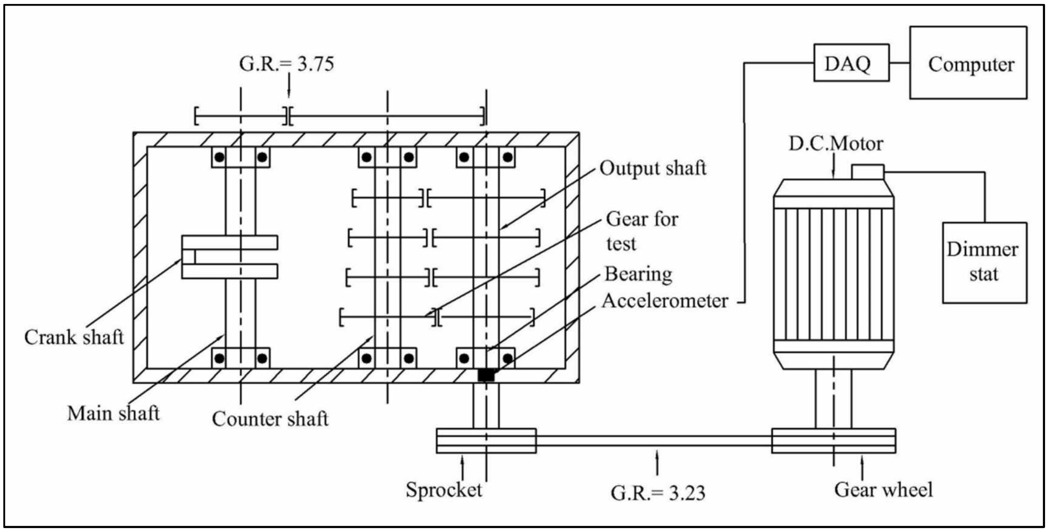


Fig.1. Line sketch experimental setup.

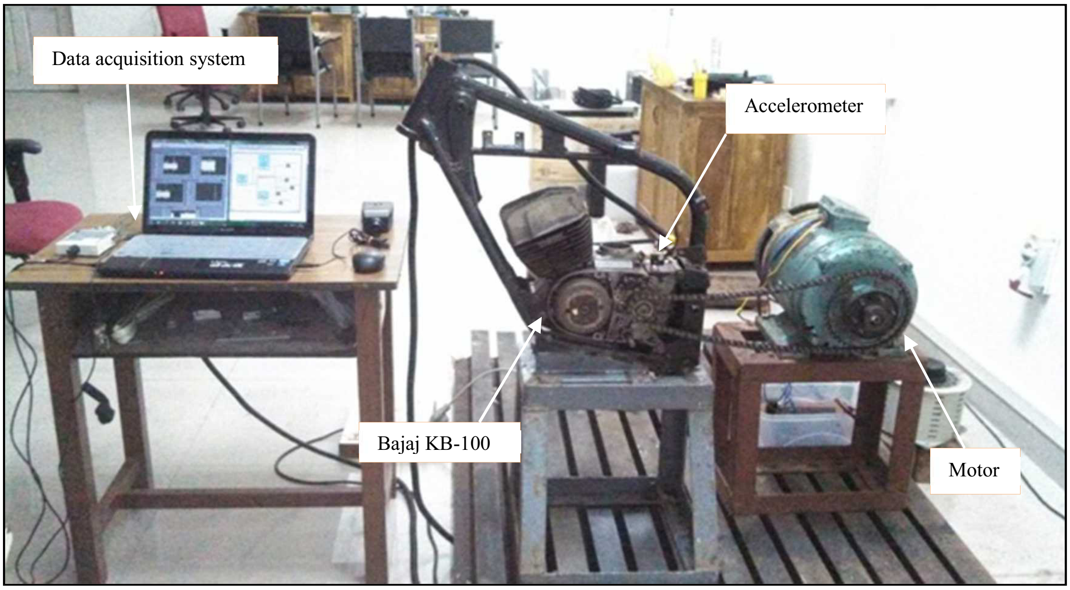


Fig. 2.Experimental set-up of gear box fault detection of an IC engine.

2.2 Experimental procedure

In this experiment, the vibration signal was acquired from a healthy gear condition at constant crank shaft speed of 1080rpm, the acquired signal is considered as the baseline. In second test, fault is induced in the gear as shown in figure 3 and the corresponding vibration readings were extracted. The sampling frequency of 5 KHz was used to collect the data for 1 second. The below figure 3show the condition and figure 4 show position of gear in the gear box. For analysis purpose, the CWT scale axis is changed to an approximate frequency axis.

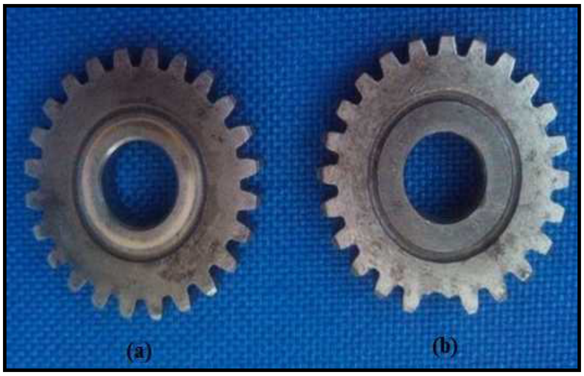


Fig.3 Gear defects.
(a)Healthy gear, (b) Gears with induced fault

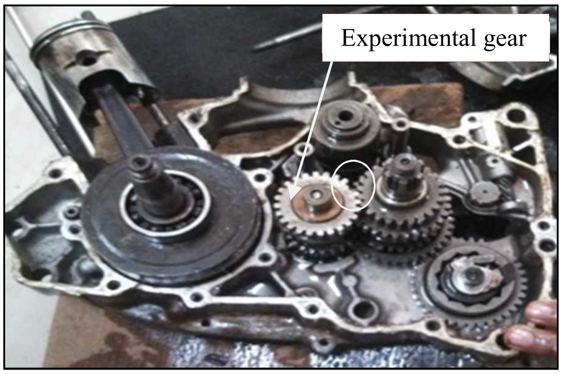


Fig.4. Sectioned view of engine

In case of gear vibration, gear mesh frequency (GMF)is important, which is generated due to modulation phenomena. In faulty condition there exists increase in magnitude in GMF which is the indication of defective condition of gear (Lokesh et al.2011). The characteristic vibration frequencies of the engine are listed in Table 1.

Table 1.Characteristic vibration frequency at 1080 rpm engine speed.

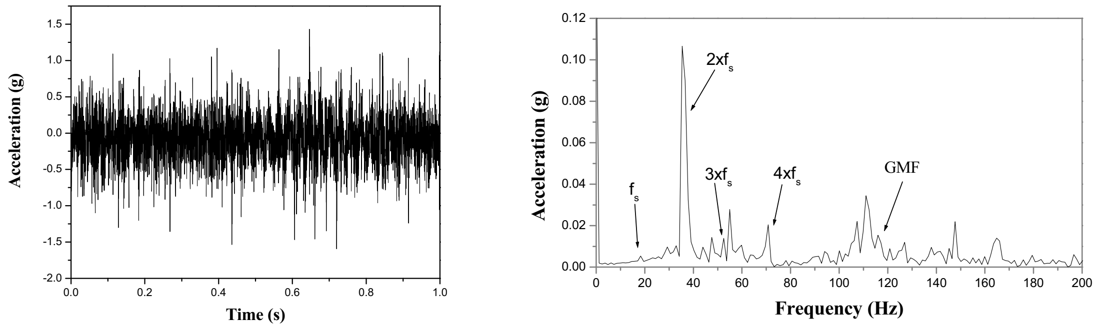
Parameters	Value (Hz)
Gear rotational frequency	4.8
Pinion rotational frequency	5
Gear mesh frequency (GMF)	117
Crank shaft rotating frequency (f_s)	18

4. Experimental verification of fault diagnosis system

In this section experimental discussion is made for fault diagnosis technique, based on the FFT and CWT for gear box of an IC engine.

4.1. Experiment 1: Healthy gear

The experimental results with healthy condition of gear are shown in following figures. Figure 5 (b) illustrates, peak frequency component at 18 Hz, which is the running frequency of the crank shaft rotation (f_s).Another frequency, is at 36 Hz ($2xf_s$)and most of the rest of the peaks are multiples of crank shaft rotating frequencies. It can be noticed from frequency spectrum that the vibration of the crank shaft has highest influence on the spectrum of the gearbox, which is dominant among all the frequencies.



(a) (b)

Fig.5: Vibration response of a healthy gear. (a) Vibration response in Time domain (b) Frequency spectrum

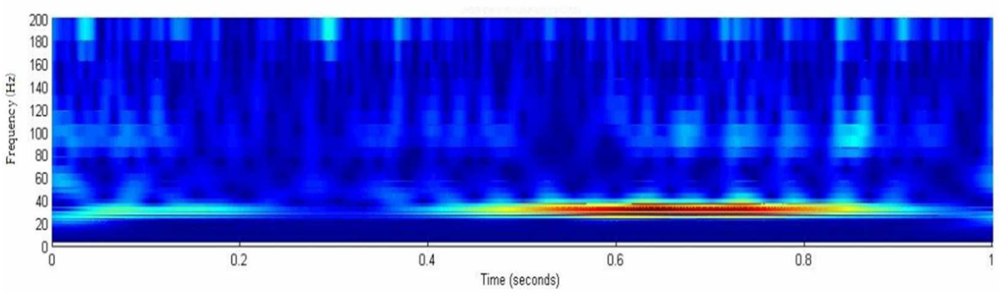
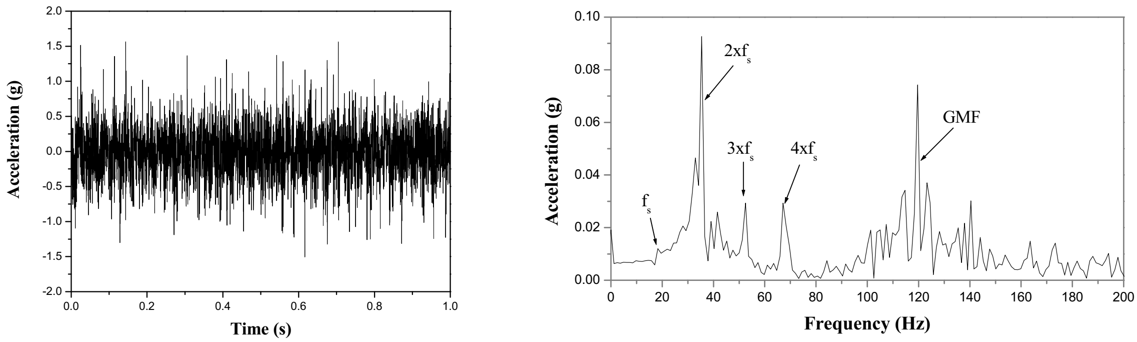


Fig.6: Time-frequency plot of the CWT of the healthy gear vibration signal

From the time-frequency plot of the CWT shown in figure 6, indicates the presence of high-frequency component at 34 Hz which is ($2xf_s$).

4.2. Experiment 2: Gear with induced fault

Figure 7 shows vibration response of faulty gear in time and frequency domain. The increase in the amplitude of GMF can be visualized in frequency domain. Magnitude of GMF is increased from 0.02 to0.08 m/s^2.



(a) (b)

Fig.7: Vibration response of a fault induced gear. (a) Vibration response in Time domain (b) Frequency spectrum

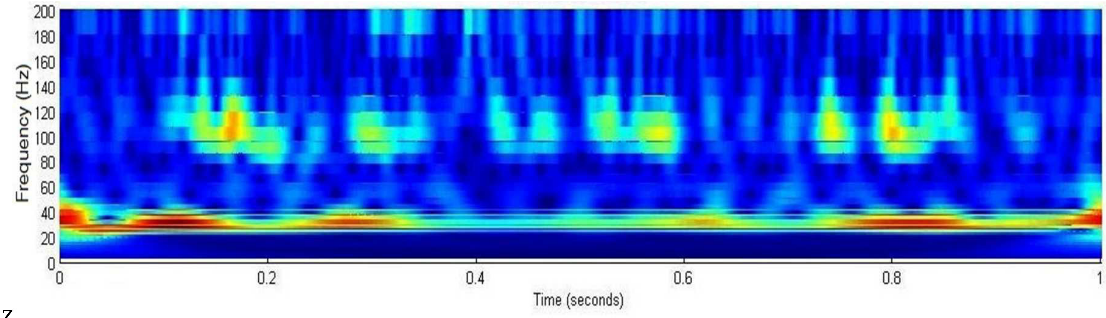


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Fig.8: Time-frequency plot of the CWT of the fault induced gear vibration signal

Figure 8 depicts CWT plot of faulty gear, which shows there is high-frequency at 34 Hz (2xf$_s$). Other than frequency 34 Hz there is one more dominant frequency component is observed at 117 Hz, which matches with the characteristic gear mesh frequency. This high-frequency band in CWT plot indicates the existence of the gear fault.

5. Conclusion

The vibration signal processing techniques using FT, CWT technique are used for fault diagnosis studies of gear damage detection. Vibration studies carried out for healthy and simulated faulty gear used in gear box of an IC engine. Vibration acceleration levels has been studied for healthy and defective gear in both time and frequency domain. Also results have been compared. CWT is used for damage detection and found that CWT is effective tool for fault diagnosis. The experimental result indicates that proposed method is effective in gear fault diagnosis. This research study can be extended to machines with a various types of faults.

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