

Value of Optimal Wavelet Function in Gear Fault Diagnosis

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ABSTRACT

Gear fault diagnosis is important in the vibration monitoring of any rotating machine. When a localized fault occurs in gears, the vibration signals always display non-stationary behavior. In early stage of gear failure, the gear mesh frequency (GMF) contains very little energy and is often overwhelmed by noise and higher-level macro-structural vibrations. An effective signal processing method would be necessary to remove such corrupting noise and interference. This paper presents the value of optimal wavelet function for early detection of faulty gear. The Envelope Detection (ED) and the Energy Operator are used for gear fault diagnosis as common techniques with and without the proposed optimal wavelet to verify the effectiveness of the optimal wavelet function. Kurtosis values are determined for the previous techniques as an indicator parameter for the ability of early gear fault detection. The comparative study is applied to real vibration signals. First, to eliminate the frequency associated with interferential vibrations, the vibration signal is filtered with a band-pass filter determined by a Morlet wavelet whose parameters are optimized based on maximum Kurtosis. Then, to further reduce the residual in-band noise and highlight the periodic impulsive feature, an envelope analysis enhancement algorithm is applied to the filtered signal. The test stand is equipped with three dynamometers; the input dynamometer serves as the internal combustion engine, the output dynamometers introduce the load on the output joint shaft flanges. The gearbox used for experimental measurements is the type most commonly used in modern small to mid-sized passenger cars with transversely mounted powertrain and front wheel drive.

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INTRODUCTION

Gears are an important element in a variety of industrial applications such as machine tool and gearboxes. An unexpected gear failure may cause significant economic losses. For that reason, the fault diagnosis of gears is important for improving mechanical system reliability and performance, and has been the subject of intensive research.

Vibration signal analysis has been widely used in fault detection on rotating machinery. Many methods based on vibration signal analysis have been developed. These methods include power spectra estimation, fast Fourier transform (FFT), and envelope spectra analysis, which have been proved to be effective in gear fault detection. However, these methods are based on the assumption of a stationary and linear vibration signal. Gear faults by their nature are time localized transient events. Therefore, new techniques are needed to analyze vibration for fault detection in gears to deal with non-stationary and non-linear signals. Time-frequency analysis techniques such as the Short Time Fourier Transform (STFT) by Cohen L. [1], Wavelet Transform (WT) by Lin J. and Qu. L. [2] and James C. Li

and Jun Ma [3] and Wigner-Ville distribution (WVD), by Staszewski W. J., Worden K. and Tomlinson G. R. [4] and Meng Q. and Qu. L. [5] are widely used. An inherent drawback of STFT is the limitation between time and frequency resolutions. The Wavelet Transform (WT), on the other hand, is similar to the STFT, in that it also provides a time-frequency map analyzed signal. STFT is limited by the size of the basic wavelet function; the downside of the uniform resolution is uniformly poor resolution. Moreover, an important limitation of (WT) is its non-adaptive nature. Once the basic wavelet is selected, one will have to use it to analyze all the data. The Wigner-Ville distribution (WVD) is a basic time-frequency representation. The difficulty with this method is the severe cross terms as indicated by the existence of negative power for some frequency ranges.

The successive impacts produce a series of impulse responses which may be amplitude modulated as a result of the passage of the fault through the load zone or of the varying transmission path between the impact point and the vibration measurement point by Ho D. and

Randall R. B. [6]. Signal modulation effect and noise are two major barriers for incipient fault diagnosis. Qiu H., Lee L., Lin J. and Yu G. [7]. To solve the problem of modulation, several signal demodulation methods have been proposed by (Randall R. B. [8] and Nikolaou N. G., Antoniadis I. A. [9]. The high-frequency resonance technique (envelope analysis) is the most widely used by (McFadden P. D., Smith J. D. [10] and Randall R. B. [6]). In practice, the signal is a band-pass filtered around one of the resonant frequencies to eliminate unwanted vibration from other sources. This signal is then demodulated by envelope detection. Finally, the spectra of the envelope signal in the low-frequency range is obtained to obtain the characteristic defect frequency. However, this method presents some disadvantages because the method requires knowledge the band filter around a resonant frequency and the method is ineffective in the presence of a high noise level by Chiementin X., Bolaers F. and Dron J. P. [11]. The wavelet transform has recently been seen as a promising alternative method due to its flexible time-frequency resolution and excellent capability for detecting transients by Nikolaou N. G., Antoniadis I. A. [12] and Altmann J., Mathew J. [13]. There are two major wavelet-based methods, wavelet decomposition-based and wavelet filter-based that can be used for mechanical fault diagnosis. The former can achieve satisfactory results on smooth signal detection while the latter is more suitable and reliable when used to detect impulse-like signatures of a mechanical defect by Qiu H., Lee J., Lin J. and Yu G. [7].

To obtain indication of a gear fault in its early stage we combined envelope detection and the Kurtosis coefficient with two different methods. A comparison result is presented of gear fault diagnosis with two methods based on Envelope Detection (ED) and Wavelet Transform (WT) using optimal Morlet wavelet function. The comparative study is applied to real vibration signals.

DESCRIPTION OF THE TEST SET-UP

Experimental Set-up

The measurements are conducted on an open loop test bed which consists of three dynamometric machines. The gearbox is screwed via flange, which normally serves for assembly with the internal combustion engine, to the test stand. The complete clutch is mounted and operated on the input shaft. The input shaft is driven via a belt drive. Original vehicle joint shafts are mounted on the output flanges. The gearbox is shifted and the clutch is operated with the aid of a shift robot. The shifting speed and shift force can be tuned for each gear. The completely newly conceived test stand can reproduce with high dynamic the data measured during real vehicle operation. However, for our purposes, we took the measurements in steady state regimes only. Fig. 1 shows the layout of the test rig components and indicates the accelerometer and tachometer positions.



Figure 1. The open loop test bed used for investigation of faults in an automotive gearbox.

Investigated Gearbox

The gearbox used for our measurements is the type most commonly used in modern small to mid-sized passenger cars with transversely mounted powertrain and front wheel drive; a five speed gearbox with final drive gear and front wheel differential. The internal arrangement of gears, shafts and bearings is depicted in Fig. 2. One fault is artificially introduced into the gearbox: a dimple to imitate pitting damage on the fifth speed pinion mounted on the intermediate or secondary shaft. The gear with the introduced fault is shown in the Fig. 2. The fifth speed gear specifications are shown in Table 1.

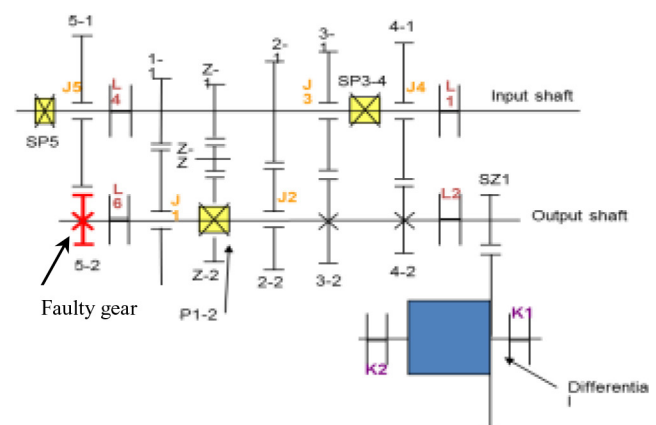


Figure 2. Diagram of the investigated five-speed automotive gearbox, the highlighted gear is the faulty element.

Table 1. Fifth speed gear specification

No.	Modal parameter	Drive gear	Driven gear
1	Location in gearbox	Input shaft	Intermediate shaft
2	No. of teeth (Z)	50	37
3	Young modulus (E=N/m2)	21e10	21e10
4	Gear case	Healthy	Faulty (Pitted)
5	Poisson's ratio (v)	0.3	
6	Transmission ratio (R _p)	0.74	

DESCRIPTION OF THE ARTIFICIAL DAMAGE

Fig. 3 shows the pinion for fifth speed with damage on one tooth only. The mesh side of the tooth was damaged by grinding one a pit as shown in the following figure. The photos and measured data of the pit were acquired with the Video-Probe XLG3 from GE Measurement & Control Systems with the aid of 3D Phase Measurement. The total surface area of the pit is 4.58 mm². The gearwheel is treated as damaged if the surface of damage on one tooth is greater than 4 % of the tooth surface. In our case the damage equals 3 % of the tooth surface. This means there is a significant pit, but the pinion gear can't yet be treated as damaged.



Figure 3. Detail of the pitting damaged created on one tooth only.

NON-STATIONARY WAVEFORM DATA ANALYSIS

Time-Frequency Analysis

One limitation of frequency-domain analysis is its inability to handle non-stationary waveform signals, which are very common when machinery faults occur. Thus, time-frequency analysis, which investigates waveform signals in both the time and frequency domain, has been developed for non-stationary waveform signals. Traditional time-frequency analysis uses time-frequency distributions, which represent the energy or power of waveform signals in two-dimensional functions of both time and frequency, to better reveal fault patterns for more accurate diagnostics. Another transform for time-frequency analysis is the wavelet transform. Generally, the wavelet transform can provide a time-frequency or time scale representation of a signal. The scale parameter can be transformed to frequency, depending on the purpose of analysis. Wavelet theory has developed rapidly over the past two decades and has a wide range of applications.

Morlet Wavelet Filter

The major advantage of wavelet analysis is the presentation of signals in time-frequency distribution diagrams with multi-resolution in time and frequency. There are many types of available wavelet function that can be used for different purposes, such as the Haar, Daubechies, Gaussian, Meyer, Mexican Hat, Morlet, Coiflet, Symlet, Bi-orthogonal and so on. Generally, Continuous Wavelet Transform (CWT) is preferable for vibration-based machine fault diagnosis, as the resolution is higher compared to the dyadic type of wavelet transform, Tse P., Peng Y. H. and Yam R. [14], and it has more freedom for selecting wavelet base function including no orthogonal wavelet. Although there is no standard method for selecting the wavelet function for different tasks, Peng Z. K., Chu F. L. [15], we can choose a proper wavelet according to practical signal characteristics. When a defect is present in a gear an impact response occurs. The typical impact response comprises an initial fast rise and a decaying part. There is a similarity between the decaying part of the Morlet wavelet and the decaying part of the typical impact generated transient. The Morlet wavelet is one of the most popular non-orthogonal wavelets. The definition of the mother Morlet is:

$$\psi(t) = \exp\left(\frac{\beta^2 * t^2}{2}\right) \cos(\pi t) \quad (1)$$

It is a cosine signal that decays exponentially on both the left and the right sides. This feature makes it very similar to an impulse. It has been used for impulse isolation and mechanical fault diagnosis through the performance of a wavelet de-noising procedure. However, in practice, it is not easy to provide a proper threshold for wavelet de-noising. This can be avoided by using an adaptive wavelet filter instead of wavelet de-noising. CWT is used for obtaining the wavelet coefficients of the signals. The statistical parameters of the wavelet coefficients are extracted which constitute the feature vectors.

Adaptive Morlet Wavelet Filter

A daughter Morlet wavelet is obtained by time translation and scale dilation from the mother wavelet, as shown in the following formula, Shensa, M. J. [16]:

$$\psi_{a,b}(t) = \psi\left(\frac{t-b}{a}\right) = \exp\left[-\frac{\beta^2(T-B)^2}{2a^2}\right] \cos\left[\frac{\pi(t-b)}{a}\right] \quad (2)$$

Where (a) is the scale parameter for dilation, and (b) is the time translation. It can also be looked at as a filter. To identify the immersed impulses by filtering, the location and the shape of the frequency band corresponding to the impulses must first be determined. Scale (a) and parameter (β) control the location and the shape of the daughter Morlet wavelet respectively. As a result, an adaptive wavelet filter could be built by optimizing the two parameters for a daughter wavelet. Several researchers have reported on how to select the mother wavelet that adapts best to the signal required to be isolated.

The method of (β) selection in the Morlet wavelet is based on maximum Kurtosis. Details on how to select β and (b) in the Morlet wavelet based on Kurtosis to make the mother wavelet match the