

Application of Optimal Morlet Wavelet Filter for Bearing Fault Diagnosis

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ABSTRACT

When localized fault occurs in a bearing, the periodic impulsive feature of the vibration signal appears in time domain and the corresponding Bearing Characteristic Frequencies (BCFs) emerge in frequency domain. The common technique of Fast Fourier Transforms (FFT) and Envelope Detection (ED) are always used to identify faults occurring at the BCFs. In the early stage of bearing failures, the BCFs contain very little energy and are often overwhelmed by noise and higher-level macro-structural vibrations. In order to extract the weak fault information submerged in strong background noise of the gearbox vibration signal, an effective signal processing method would be necessary to remove such corrupting noise and interference. Optimal Morlet Wavelet Filter and Envelope Detection (ED) are applied in this paper. 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 the maximum Kurtosis value. Then, to further reduce the residual in-band noise and highlight the periodic impulsive feature, an envelope enhancement is applied to the filtered signal. The proposed and the common techniques are used respectively to analyze the experimental signal with inner race fault of rolling bearings. The test stand is equipped with two dynamometers; the input dynamometer serves as internal combustion engine, the output dynamometer introduce the load on the flange of output joint shaft. The Kurtosis and pulse indicator are chosen as the evaluation of the denoising effect. The results of comparative analysis have drawn that the proposed technique is more accurate and reliable than the common technique for the fault feature extraction. Especially, it is much easier to achieve early diagnosis for bearing failure.

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INTRODUCTION

Bearings are an important element in a variety of industrial applications such as machine tool and gearbox. An unexpected failure of the bearing may cause significant economic losses. For that reason, the fault diagnosis of bearing 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 the faults detection of rotating machinery. Many methods based on vibration signal analysis have been developed. These methods include power spectrum estimation, fast Fourier transform (FFT), envelope spectrum analysis, which have been proved to be effective in bearing fault detection. However, these methods are based on the assumption of stationary of the vibration signal. Therefore, new techniques are needed to analyze vibration for faults detection in ball bearing. Bearing faults by their nature are time localized transient events. To deal with non-stationary and non-linearity signals, time-frequency analysis techniques such as the Short Time Fourier Transform (STFT) [1], Wavelet Transform (WT) [2, 3, 4] and Wigner-Ville distribution (WVD) [5, 6] are widely used. An inherent

drawback with the STFT is the limitation between time and frequency resolutions. The Wavelet Transform (WT), on the other hand, is similar to the SHFT in that it also provides a time-frequency map of the signal being analyzed. Limited by the size of the basic wavelet function, the downside of the uniform resolution is uniformly poor resolution. Moreover, an important limitation of the wavelet analysis 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 [8]. Signal modulation effect and noise are two major barriers in incipient fault diagnosis [9]. To solve the problem of modulation, several signal demodulation methods have been proposed [10, 11, 12]. The high-

frequency resonance technique (envelope analysis) is the most widely used [7, 10]. In practice, the signal is band-pass filtered around one of the resonance frequencies to eliminate unwanted vibration from others sources. Then this signal is demodulated by the envelope detection. Finally, the spectrum of the envelope signal in the low-frequency range is obtained to get the characteristic defect frequency. However, this method presents some disadvantages because the method requires us to know the band filter around a resonance frequency [14]. Recently, the wavelet transform has been a promising alternative method for its flexible time-frequency resolution and excellent capability of detecting transients [12, 13, 14, 15, 16, 17, 18]. There are two major wavelet-based methods, that is, wavelet decomposition-based and wavelet filter-based, to be used for mechanical fault diagnosis. The former can achieve satisfactory results on smooth signal detection while the latter is more suitable and reliable to detect impulse-like signatures of mechanical defect [9].

The presented research is focused especially on: application of optimal wavelet based on maximum Kurtosis in bearing fault diagnosis. The article is organized as, full description of experimental set-up, brief description of investigated gearbox and detail of artificial defect. Signal processing techniques are used in the proposed method. Subsequently, Illustrate the vibration measurement and results. Finally, discussion and conclusion

DESCRIPTION OF THE TEST SET-UP

Experimental Set-Up

The measurements are conducted on an open loop test bed consisting of two dynamometric machines, the gearbox to be tested, and torque flanges for torque measurement. On the input, as the internal combustion engine, is used a three-phase dynamometer KS 56-4. On the output side is an eddy current water cooled dynamometer 2VD 110 / 6 as a brake as shown in Figure 1. To obtain a wide range of rotation speeds we use a planetary two speed overdrive unit after the input dynamometer. The planetary gear set can function as direct with ratio = 1 or overdrive (ratio = 0.4). The shift of the overdrive unit can only occur in steady state. In our case, we used the ratio = 1 in the planetary gearbox. When the gearbox for transversal disposition of drivetrain is used - in the case of the investigated gearbox - the differential has to be locked. The power flows through one output shaft only. The test stand is existed in the laboratory of Czech Technical University in Prague - is depicted on Figure 1.

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 two-shaft, five speed gearbox with final drive gear and front wheel differential. The internal arrangement of gears, shafts and bearings is depicted in Figure 2. One fault is artificially introduced into the gearbox: groove on the inner race of a bearing mounted on the input shaft in the clutch casing (the faulty bearing is highlighted in the Figure 2).

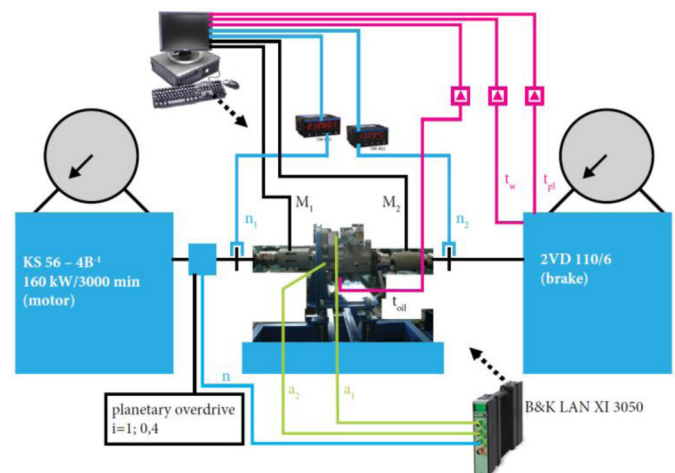


Figure 1. Diagram of the open loop test bed used for investigation of fault in an automotive gearbox.

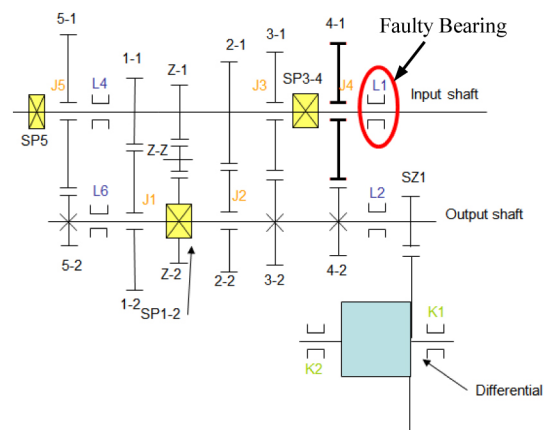


Figure 2. Diagram of the investigated five-speed automotive gearbox, the highlighted bearing is the faulty element.

The following Figure depicts the artificially fabricated fault, only one defect has been investigated, while our aim was the early fault detection and not classification, an artificial defect was used to control the defect size. In the case of the bearing a groove was orthogonally grinded on the inner race of the roller bearing on the input shaft. The width of the groove varies from 0.6 mm. The diameter of the rollers is 4 mm, so a groove of these dimensions produces a significant impact on the rollers, which will be demonstrated, where the results of vibration measurements are discussed.

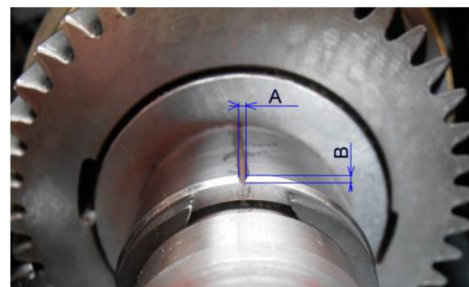


Figure 3. Detail of the bearing inner race damage. A = 0.6 mm, B = 0.6 mm.

SIGNAL PROCESSING

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. The 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. Short-Time Fourier Transform (STFT) or spectrogram (the power of STFT) and Wigner-Ville distribution are the most popular time-frequency distributions [19]. Another transform for time-frequency analysis is the wavelet transform. Generally, 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 the analysis. Wavelet theory has developed rapidly over the past two decades and has a wide range of applications.

Envelope Signal Processing

Envelope Signal Processing is a two-stage process. The first process involves band-pass filtering of the time domain signal using a band pass filter that centers on the region of high frequency energy. The filtered output is in the time domain of the original signal. The frequency domain is also shown to aid the understanding of the process. The filtering process results in a series of spiky bursts of energy, which are the impacts from the rolling elements hitting the defect as the bearing rotates. The second stage of the process is to pass this filtered time signal through an envelope in order to extract the repetition rate of the spiky bursts of energy. The envelope is an electronic circuit that demodulates or rectifies the signal. The result of passing the signal through the envelope: The extracted signal is the repetition rate of the impacts. If the FFT spectrum of this enveloped signal is then taken, it displays the bearing characteristics frequency and its harmonics. Therefore, the envelope detection technique should be used together with FFT to ensure that the impulsive frequency of BCFs can be more easily found.

Morlet Wavelet Filter

FFT does not give a simultaneous representation in the time and frequency domains. Moreover, FFT cannot capture non-stationary signals. Thus, it is handicapped in detecting impulses generated by the random contacts of defective surfaces. 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 wavelet function available to use for different purpose, 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 with the dyadic type of wavelet transform, and has more freedom for selecting wavelet base function including no orthogonal wavelet. Although there is not a standard method to select the wavelet function for different tasks [20], we can choose a proper wavelet

according to practical signal characteristic. When, a defect is present in rolling bearing an impact response occurs. The typical impact response comprises an initial fast rise and a decaying part. There is similarity between the decaying part of the Morlet wavelet and the decaying part of the typical impact generated transient. Morlet wavelet is one of the most popular non-orthogonal wavelets. The definition of Morlet is [23]:

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

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 [21]:

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

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 be determined first. 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 the best to the signal to be isolated. The method of (β) selection in Morlet wavelet is based on maximum Kurtosis. Details on how to select (β) and (a) in Morlet wavelet based on Kurtosis to make the mother wavelet match the signal to be isolated are provided in [21, 22]. The procedure to perform the adaptive wavelet filtering is provided in [23].

Fault Bearing Characteristic Frequencies (BCFs)

Each bearing element has its own characteristic frequency of defect. Those frequencies can be calculated from the kinematic relations, i.e., the geometry of the bearing and its rotating speed. For a bearing with a stationary outer race, the above defect characteristic frequencies can be obtained as follows [14]: