

Distinction of Roller Bearing Defect from Gear Defect via Envelope Process and Autocorrelation Enhancement

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ABSTRACT

Bearing and gear condition monitoring are important to improve a mechanical system reliability and performance. In the early stage of bearing failures, the Bearing Characteristic Frequencies (BCFs) contain very little energy and are often overwhelmed by noise and higher-level macro-structural vibrations, an effective signal processing method would be necessary to eliminate such corrupting noise and interference. Referring to the non-stationary characteristics of roller bearing fault vibration signals, a roller bearing condition monitoring method based on Envelope Process to raw time-domain vibration signal and Autocorrelation enhancement to the residual signal is put forward in this paper. The concept of Envelope and Autocorrelation techniques and its implementation for defect identification are discussed. Also, distinction of bearing fault signal as cyclostationary from periodic signal for gear fault. An automotive gearbox is used on the test stand, which is equipped with three dynamometers; the input dynamometer serves as internal combustion engine, the output dynamometers introduce the load on the flanges of output joint shafts. This assertion is demonstrated by introducing an experimental study on artificial defects in one roller element of bearing on the input shaft and pinion gear tooth on the secondary shaft. The proposed method remains the periodicity of the characteristic features (repetitive patterns) of faulty bearing for lower frequency defects, which is very simple for operator to identify the bearing fault type. The results obtained from practical experiments prove that the proposed approach is very effective for distinction of roller bearing defect from gear fault.

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INTRODUCTION

Both Envelope Spectral and Autocorrelation techniques rely heavily on the identification of high frequency structural resonances which modulate the impulses generated by bearing elements striking the faults. It is often difficult to carry out such analyses when structural resonances are not readily identifiable or they are located within the bandwidth of gear mesh harmonics which are larger in amplitude than the bearing signals. A typical example is bearing fault detection of a vehicle gearbox, where the gear mesh vibration extends into the high frequency range and interacts with bearing fault related vibrations. In simple cases where gear and bearing signals are purely additive, it is probably not very difficult to separate them. But the gear and bearing signals interaction are most likely to be multiplicative because gear mesh vibration signal has to pass through bearings to vibration sensor. Various fault detection methods have been proposed and developed, ([1] Park et al. 2013) have classified these Methods into four groups with respect to the domain which have observed. First, Spectral Analysis ([2] Taylor 1980), and its various application methods are utilized widely: Directional Spectrum ([3] Lee and Park 1999), Moving Window Method ([4] Kim et al. 1991), Spectral Kurtosis ([5] Sawalhi, et al. 2007 and [6] Lei, et al. 2011), and Energy Spectrum by amplitude demodulation,

([7] Liang and Bozchalooi 2010). Second, Cepstral Analysis, which includes Power Cepstrum ([8] Ho, et al 1999 and [9] Randall, et al 1987), Minimum Variance Cepstrum ([10] Choi and Kim 2007) etc., is used for the detection of fault periods in the quefrency domain. Third, it has been observed by Envelope Analysis e.g. High Frequency Resonance Technique ([11] Randall, New 1982 and [12] Mc Fadden, Smith 1984), Complex Envelope ([13] Kim et al.1988 and [14] Ming, et al. 2011), etc.). Finally, Time-Frequency Analysis, which is known as an efficient way to detect transient signals, has been suggested. In particular, Wavelet Analysis has recently been widely applied to fault detection because of good resolution on some scales and also in time for example, ([15] Peng, Chu 2004, [16] Abbasian, et al. (2007), [17] Bozchalooi, Liang 2008 and [18] Su et al. 2010). In addition, Lee and White ([19] Lee and White 1998) proposed the Active Noise Cancellation Algorithm and Machinery Diagnostic Method. The Cyclostationary Approach ([20] McCormick, Nandi 1998, [21] Capdessus, et al. 2000, [22] Randall, et al. 2001 and [23] Randall, Antoni 2002) has also been employed for fault detection. Although, many detecting algorithms have been proposed, most of them can be classified into these four groups. Improve for traditional Envelope detection by applying an original Wavelet filter has been discussed ([24] M. El Morsy and G. Achtenová) for inner

race of roller bearing. The Main idea of the present work is to recognize bearing fault signal (roller element fault) which is restrained by faulted gear signal (pitted tooth). Most of the previous work has been dealt with the vibration-based diagnosis of rolling element bearings and gears separately. The present work deals with the vibration-based diagnosis of rolling element bearings in the presence of strong interfering gear signals, such as is typical of vehicle gearbox, and the key idea consists in recognizing faulty bearing signals from the faulty gear signals. This assertion is demonstrated by introducing artificial defects in a bearing in clutch casing on input shaft and pinion gear in fifth speed on output shaft for automotive gearbox. The present proposed method is based on Envelope Process to raw time-domain vibration signal and Autocorrelation enhancement to the residual signal.

The presented paper is organized as follows: the proposed fault signature theories are briefly mentioned. The test set-up and seeded fault geometry are described and stated the bearing own characteristic frequency equations (BCFs). Vibration measurement technique, equipment characteristics and results are discussed. Finally, the discussion and the experimental results validate the efficiency of the proposed technique.

SIGNAL PROCESSING

Envelope Process

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 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 envelop analyzer is an electronic circuit that demodulates or rectifies the signal. The result of passing the signal through the envelop analyzer: 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.

Applications of Envelope Analysis Are in

- Roller bearing elements: Identification of cracks in inner race, outer race or roller defects
- Gear boxes: Identification of cracked or broken teeth from impulsive modulation of the tooth meshing frequency
- Turbine blades: Identification of broken or distorted blades from modulation of the blade passing frequency
- Induction motors: Identification of broken or cracked rotor bars, or bad soldering from modulation of slot harmonics by twice the slip frequency
- Reciprocating machinery: Determination of precise point (in time) in the cycle of impulsive events like valve openings/closings or combustion.

Autocorrelation Algorithm

Autocorrelation is the Cross-correlation of a signal with itself. Informally, it is the similarity between observations as a function of the time separation between them. It is a mathematical tool for finding repeating patterns, such as the presence of a periodic signal which has been buried under noise, vibration, or identifying the missing fundamental frequency in a signal implied by its harmonic frequencies. It is often used in signal processing for analyzing functions or series of values, such as time domain signals.

The strength of the Autocorrelation function is its ability to identify low repetition rate events with low duty cycle and the ability to separate random events from periodic events. The Autocorrelation function can be written as ([25] Gardner 1986):

$$R_{xx}(\tau) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_{-T}^T X(t) X(t + \tau) dt \quad (1)$$

DESCRIPTION OF THE TEST SET-UP

Experimental Set-Up



Test rig arrangement

Vehicle gearbox

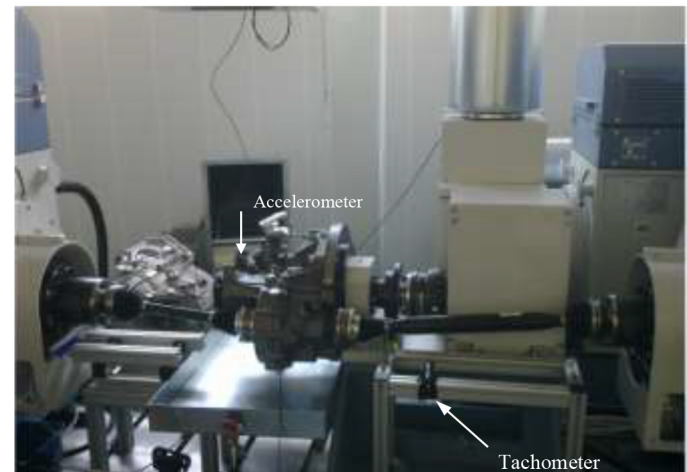


Figure 1. An open loop test bed used for investigation of faults in an automotive gearbox with the aid of vibration measurement.

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. On the input shaft is mounted and operated the complete clutch. The drive of the input shaft is ensured via belt drive. On the output flanges are mounted original vehicle joint shafts. The gearbox is shifted and the clutch is operated with help of 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 the real drive of the vehicle. Anyhow for our purpose, we did the measurements in steady state regimes only. Figure 1 shows the real photo of arrangement layout of test rig components and indicates to the accelerometer and tachometer positions.

Investigated Gearbox

The gearbox used for the measurements is the type most commonly used in current small and mid-size passenger cars with transversally 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 Figure 2. Two faults on one roller of the bearing are artificially introduced into the gearbox. Next fault in the gearbox is introduced on the pinion gearwheel: grinded pit on the free rotating gear of the fifth speed. The bearing and pinion gear with the introduced faults are marked in red on the Figure 2.

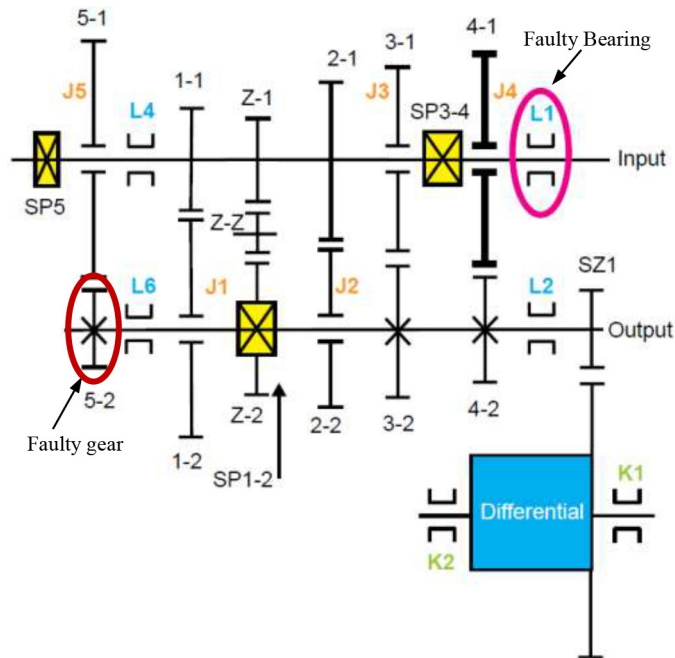


Figure 2. Diagram of the investigated five-speed automotive gearbox, the highlighted are the faulty elements.

Description of the Artificial Damage

Figure 3(upper) 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. 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 (lower) shows the two faults on one roller of the bearing are artificially introduced: Two dimples which, one small imitates a

pitting damage, second corresponds to the longitudinally flatten surface on one half of the length of the rolling element of rolling bearing mounted on the input shaft.

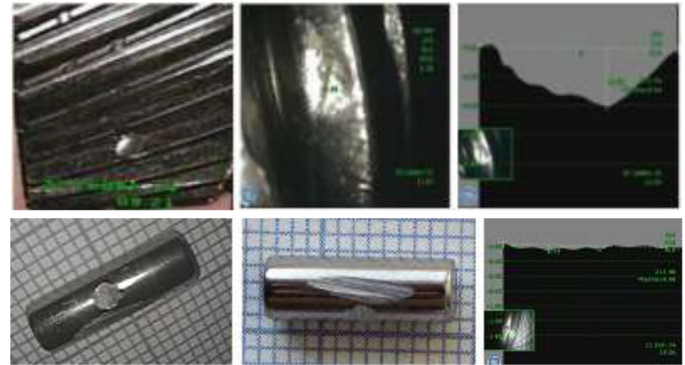


Figure 3. Detail of the pitting created on one gear tooth (upper) and one roller element of bearing (lower)

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]:

Characteristic frequency of the outer-race:

$$f_o(\text{in Hz}) = \frac{zf}{2} \left(1 - \frac{d}{D} \cos \alpha \right) \quad (2)$$

Characteristic frequency of the inner-race:

$$f_i(\text{in Hz}) = \frac{zf}{2} \left(1 + \frac{d}{D} \cos \alpha \right) \quad (3)$$

Roller (BPFR) or the Ball Spin Frequency (BSF):

$$f_r(\text{in Hz}) = \frac{D}{d} f \left[1 - \left(\frac{d}{D} \cos \alpha \right)^2 \right] \quad (4)$$

Characteristic frequency of the cage:

$$f_c(\text{in Hz}) = \frac{f}{2} \left[1 - \frac{d}{D} \cos \alpha \right] \quad (5)$$

Where f is the relative rotating frequency between inner and outer races, α is the contact angle between the race and the roller, z is the number of rollers, d is the roller diameter and D is the bearing's pitch diameter. This equation is based on the assumption of a pure rolling motion. However, in reality, some sliding motion may occur, which