Teager Energy Spectrum for Fault Diagnosis of Rolling Element Bearings

Zhipeng Feng\(^1\), Tianjin Wang\(^1\), Ming J. Zuo\(^2\), Fulei Chu\(^3\) and Shaoze Yan\(^3\)

\(^1\) School of Mechanical Engineering, University of Science and Technology Beijing
Beijing 100083, China
E-mail: zhipeng.feng@yahoo.com.cn
\(^2\) Department of Mechanical Engineering, University of Alberta
Edmonton, Alberta T6G 2G8, China
\(^3\) Department of Precision Instruments and Mechatronics, Tsinghua University
Beijing 100084, China

Abstract. Localized damage of rolling element bearings generates periodic impulses during running. The repeating frequency of impulses is a key indicator for diagnosing the localized damage of bearings. A new method, called Teager energy spectrum, is proposed to diagnose the faults of rolling element bearings. It exploits the unique advantages of Teager energy operator in detecting transient components in signals to extract periodic impulses of bearing faults, and uses the Fourier spectrum of Teager energy to identify the characteristic frequency of bearing faults. The effectiveness of the proposed method is validated by analyzing the experimental bearing vibration signals.

1. Introduction

Rolling element bearings play a crucial role in mechanical systems, and is one of the most commonly used mechanical components. They often work in harsh environment with heavy load, and therefore are one of the most failure-prone mechanical elements. Hence, it is important to conduct fault diagnosis research for rolling element bearings.

The faults of rolling element bearings are often caused by surface damage, such as spalls or cracks on outer race, inner race or rolling elements. When damaged area comes into contact with the mating surfaces during running, a periodic impulse train will be generated. The repeating frequency of impulses equals the characteristic frequency of bearing element fault [1-3]. Therefore, how to extract the repeating frequency of periodic impulse train is a key issue for fault diagnosis of rolling element bearings.

Teager energy operator presented in the nonlinear signal processing community provides a good potential to extract the fault induced impulses. In this paper, the Fourier spectrum of Teager energy is used to identify the repeating frequency of impulse train, and thereby to diagnose bearing faults.

2. Teager Energy Spectrum

2.1. Teager Energy Operator

Teager Energy operator is originally proposed for non-linear speech processing. For a continuous time signal \(x(t)\), Teager energy operator \(\Psi\) is defined as [4-7]

\[
\Psi[x(t)] = \frac{1}{2} [x(t)]^2 - x(t)\dot{x}(t),
\]

(1)
where $\dot{x}(t)$ and $\ddot{x}(t)$ are the first and the second derivative of $x(t)$ with respect to time $t$, respectively. It can track the total energy required to generate the signal $x(t)$.

Considering an undamped linear mass-spring oscillator with mass $m$ and spring stiffness $k$, according to Newton’s theorem, a second-order differential equation governing the motion of the mass can be obtained as

$$m\ddot{x}(t) + kx(t) = 0,$$

where $x(t)$ is the displacement of the mass measured from its equilibrium position.

The solution to equation (2) is a simple harmonic vibration given by

$$x(t) = A\cos(\omega t + \theta),$$

where $A$ is the vibration amplitude, $\omega = \sqrt{k/m}$ is the natural frequency of the vibration system, and $\theta$ is an arbitrary initial phase. Accordingly, its first and second derivative can be obtained as

$$\dot{x}(t) = -A\omega\sin(\omega t + \theta),$$

$$\ddot{x}(t) = -A\omega^2\cos(\omega t + \theta).$$

The total mechanical energy of the system is the sum of the potential energy in the spring and the kinetic energy of the mass

$$E = \frac{1}{2}k[x(t)]^2 + \frac{1}{2}m[\dot{x}(t)]^2.$$  

Substituting equations (3) and (4) into equation (6), it gives

$$E = \frac{1}{2}mA^2\omega^2.$$  

Equation (7) states that the total mechanical energy of the simple harmonic vibration is proportional not only to the square of the vibration amplitude but also to the square of the vibration frequency.

Applying Teager energy operator $\Psi$ to equation (3), it gives

$$\Psi[x(t)] = \Psi[A\cos(\omega t + \theta)] = A^2\omega^2.$$  

Equation (8) says that the output of Teager energy operator tracks the total energy of the source generating the vibration signal $x(t)$ in a sense of per half-unit mass.

For a discrete time signal $x(n)$ (where $n$ is the discrete time index), using difference to approximate differential, Teager energy operator can be revised as

$$\Psi[x(n)] = [x(n)]^2 - x(n-1)x(n+1).$$

It can be seen that at any instant, only three consecutive samples are needed to calculate the instantaneous Teager energy required to generate the signal. Therefore, it has a good adaptability to the instantaneous changes in signals and an excellent ability to resolve transient events.

2.2. Teager Energy Spectrum

When localized damage on a bearing element contacts the mating elements during running, it breaks up the oil film between the two contacting surfaces, and thus induces a sudden change in vibration energy and generates periodic impulse train. The impulse will further excite the resonance of bearings which is decaying and goes at a high frequency.

The output of Teager energy operator equals the squared product of both instantaneous amplitude and instantaneous frequency. In comparison to the conventional energy which equals the square of instantaneous amplitude only, it has an additional term which is the squared instantaneous frequency. Since the impulse induced vibration goes at high resonance frequency, Teager energy has a bigger value at the instant when an impulse occurs, and therefore is more powerful to highlight and detect impulses.

The repeating frequency of impulse train reflects the location of bearing faults. According to this principle, Teager energy spectrum is proposed for fault diagnosis of bearings. Firstly, Teager energy operator is applied to signals to detect impulses, using its merits in identifying transient events in signals. Then, Fourier transform is applied to the calculated Teager energy series, to identify the
periodicity of impulses. Finally, according to the characteristic frequency of each element fault and the prominent frequencies in the Teager energy spectrum, the fault can be diagnosed.

In the following sections, the proposed method will be used to analyze the experimental bearing vibration signals to show its performance.

3. Experimental Signal Analysis

3.1. Experimental Settings

The bearing to be tested is a GB6220 deep groove ball bearing. Its parameters are listed in Table 1. To simulate various types of damage in rolling element bearing, the outer race, inner race and one ball is seeded a single pit in size of 2.0mm diameter and 1.0mm depth respectively by electro-discharge machining, as shown in Figure 1.

Table 1. Parameters of bearing GB6220.

| Inner diameter | Outer diameter | Ball diameter | Number of balls | Contact angle |
|----------------|----------------|---------------|----------------|--------------|
| 100 mm         | 180 mm         | 25.4 mm       | 10             | 0°           |

Figure 1. Seeded damage on bearing elements.

Figure 2 shows the bearing test setup. A shaft is supported by two journal bearings and driven by an AC motor through a V-belt of transmission ratio 1:1. The rolling element bearing to be tested is mounted at the output end of the shaft. A two-step loading lever mechanism is employed to apply load to the tested bearing. An accelerometer is mounted at the top of bearing casing.

Figure 2. Bearing test rig.

During the experiment, the rotating speed of the drive motor is 444 rpm, the load applied on the tested bearing is 15.68kN, and accelerometer signals are collected at a sampling frequency of 10 kHz under one normal status and three faulty statuses (with damage on outer race, inner race and one ball respectively).

According to the parameters of bearing GB6220, the characteristic frequency of each faulty bearing element can be calculated respectively, as listed in Table 2.

Table 2. Characteristic frequency of bearing GB6220 [Hz].

| Ball pass frequency on outer race | Ball pass frequency on inner race | Ball spin frequency |
|----------------------------------|----------------------------------|--------------------|
| 30.97                            | 43.03                            | 22.12              |
3.2. Normal Bearing

The bearing vibration signal under normal status is analyzed firstly, to get a baseline for comparison study. Figure 3 (a)-(d) show the waveform, power spectrum, instantaneous Teager energy, and Teager energy spectrum respectively. The peaks in the power spectrum and the energy operator spectrum do not correspond to the characteristic frequency of any bearing element fault. This indicates that the bearing is perfect.

![Waveform](a) Waveform  ![Power spectrum](b) Power spectrum
![Instantaneous Teager energy](c) Instantaneous Teager energy  ![Teager energy spectrum](d) Teager energy spectrum

Figure 3. Normal bearing signal.

3.3. Faulty Bearings

In the following sections, Teager energy spectrum is applied toanalyzing the vibration signal under the status of damaged outer race to illustrate its effectiveness firstly, and then to analyze the signals under the statuses of damaged inner race and ball to show its performance in extracting weak symptoms.

3.3.1. Outer race damage. Usually, the outer race of a bearing is fixed to the bearing housing, and sensor is mounted on the housing. So the transfer path for the outer race damage induced vibration signal going to the sensor is short and fixed. In this sense, there is relatively less interference to the damage signature. Therefore, the outer race damage often exhibits significant symptom, and it is easier to be diagnosed.

Figure 4 shows the analysis results of the bearing vibration signal with damaged outer race. In the power spectrum, some sidebands appear in the frequency band from 200 Hz to 1000 Hz, and the sideband spacing corresponds to the characteristic frequency of outer race fault. However, in the Teager energy spectrum, the characteristic frequency of outer race fault and its harmonics are present directly. Therefore, it is much easier to diagnose the outer race damage and interpret the symptom observing the Teager energy spectrum.
3.3.2. Inner race damage. The inner race of rolling element bearings is usually tied to and rotates with the shaft which it is supporting. The relative position of the damage on inner race to the sensor is altering with the running of bearings. So the transfer path for the inner race damage induced vibration signal going to the sensor is altering and longer. In this sense, more factors get involved in interfering the damage signature. Therefore, the inner race damage often has weak symptom, and it is difficult to be diagnosed.

Figure 5 shows the analysis results of the bearing vibration signal with damaged inner race. Some sidebands appear in the frequency band from 200 Hz to 1000 Hz, and the sideband spacing correspond to the characteristic frequency of inner race fault. In the Teager energy spectrum, the fault symptom is more significant: the characteristic frequency of inner race fault and its harmonics are present.
3.3.3. **Ball damage.** In rolling element bearings, rolling elements not only spin around their own centers but also revolve with the ball cage around the supported shaft. So the relative position of the damage on ball to the sensor is also altering during the running of bearings. These factors make the transfer path for the ball damage induced vibration signal going to the sensor to be most complicated. In this sense, much more factors get involved in interfering the damage signature. Therefore, the ball damage often has very weak symptom, and it is very difficult to be diagnosed.

Figure 6 shows the analysis results of the bearing vibration signal with a damaged ball. The power spectrum shows a similar structure to that of the normal bearing signal. This might result in mistakes when identifying the health status of the bearing. However, in the Teager energy spectrum, the characteristic frequency of rolling element fault and its harmonics are very prominent. This indicates that the damage occurs on a ball.

All the above analysis results based on the proposed Teager energy spectrum are consistent with the actual settings in the experiments. It shows the effectiveness of the proposed Teager energy spectrum in diagnosing bearing faults, especially in detecting and locating the inner race and ball faults which often exhibit weaker symptoms.
4. Conclusions
In this paper a new method based on Teager energy operator is proposed to diagnose bearing faults. The method involves a simple energy operator and a Fourier transform step. Teager energy operator is firstly applied to signals to detect impulses; then Fourier transform is applied to the calculated instantaneous Teager energy series to identify the repeating frequency of impulses, obtaining Teager energy spectrum; finally, according to the prominent frequencies and the characteristic frequency of bearing element fault, the bearing fault can be diagnosed. The experimental bearing signal analysis results show that the proposed method is effective in extracting the characteristic frequency of bearing element faults, especially in identifying the weaker symptoms of inner race and rolling element faults.

5. References
[1] McFadden P D and Smith J D 1984 Model for the vibration produced by a single point defect in a rolling element bearing Journal of Sound and Vibration 96 69
[2] Tandon N and Choudhury A 1999 A review of vibration and acoustic measurement methods for the detection of defects in rolling element bearing Tribology International 32 469
[3] Feng Z P, Liu L and Zhang W M et al 2008 Fault diagnosis of bearing rolling element bearings base on wavelet time-frequency frame decomposition Journal of Vibration and Shock 27 110
[4] Kaiser J F 1990 On a simple algorithm to calculate the ‘energy’ of a signal Proceedings of IEEE International Conference on Acoustics, Speech, and Signal Processing p381
[5] Maragos P, Kaiser J F and Quatieri T F 1994 On amplitude and frequency demodulation using energy operators IEEE Transactions on Signal Processing 41 1532
[6] Bovik A C, Maragos P and Quatieri T F AM-FM energy detection and separation in noise using multiband energy operators 1993 IEEE Transactions on Signal Processing 40 3245
[7] Liang M and Soltani B I 2009 An energy operator approach to joint application of amplitude and frequency-demodulation for bearing fault detection Mechanical Systems and Signal Processing 24 1473

Acknowledgements
This work is supported by National Natural Science Foundation of China (51075028, 50705007), Scientific Research Foundation for Returned Overseas Chinese Scholars, Ministry of Education, Beijing Natural Science Foundation (3102022), and Natural Sciences and Engineering Research Council of Canada.