A Modified Sideband Energy Ratio for Fault Detection of Planetary Gearboxes

Mian Zhang, Dongdong Wei, Kesheng Wang and Ming J. Zuo

Abstract The sideband energy ratio (SER) method has been proved effective for fixed-shaft gearbox fault detection. In this paper, we utilize a reported model of the vibration signal from a planetary gearbox and derive a modified sideband energy ratio (MSER) indicator for fault detection of planetary gearboxes. In addition, recognizing that measured speed variations are inevitable even a constant speed is set at a constant level, we have considered a bandwidth of frequencies instead of a single frequency when the MSER is computed. Lab experimental data analysis demonstrates that the proposed MSER is effective in separating the health conditions of healthy, tooth crack, and tooth pitting of the sun gear of a planetary gearbox. Future research directions include other faults of planetary gearboxes and dynamic speed conditions.

1 Introduction

Gearboxes are widely used to transmit power and motion. The commonly used configurations of gearboxes include fixed shaft gearboxes and planetary gearboxes. Due to their unique physical characteristics, planetary gearboxes are extensively used in aerospace, automotive, and heavy industry applications such as helicopters, wind turbines, heavy trucks and mining equipment [1, 3, 6, 10].

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Planetary gearboxes have a compact mechanical structure and provide a large transmission ratio. Therefore, they are often used in high output power requirement transmission systems [2]. Due to the heavy load and harsh working environment, key components of planetary gearbox, such as gears, may experience damages such as crack, spalling, and pitting. These damages may lead to undesirable dynamic behaviours such as intensive vibration, serious performance reductions, and even major breakdowns [5].

Vibration monitoring for early fault detection of both fixed-shaft and planetary gearboxes has attracted considerable research interest. When such gearboxes work under relatively constant speed conditions, frequency domain methods are widely used for fault detection. Due to the complicated motion dynamics of many moving parts in planetary gearboxes, early fault detection for planetary gearboxes is much more challenging than for fixed-shaft gearboxes.

For a fixed-shaft gearbox in a wind turbine, Hanna [4] used the Sideband Energy Ratio (SER) for gear fault detection. The method was demonstrated to be able to not only detect the presence of gear damage but also pin point to the gear experiencing the damage. Pattabiraman [9] used SER to monitor gear damage progression in a fixed shaft gearbox in a wind turbine. Their case study also demonstrated that SER was a reliable defect detection parameter for tracking defect progression of a gear in fixed shaft gearboxes.

However, for planetary gearboxes, there are several problems when applying SER for fault detection. First of all, the selection of sidebands is not as straightforward. The complicated frequency spectrum has several sidebands around the central meshing frequency. For example, the planet rotating frequency and the carrier rotating frequency don't exist in fixed-shaft gearboxes. Second, the physical meaning of SER for the vibration signal collected from a planetary gearbox needs to be provided. Last, a method for bandwidth selection of the central frequency and the sideband frequencies need to be developed. Considering practical speed variations even under relatively constant speed conditions, it is necessary to consider the energy contained in a bandwidth rather than only at a single peak point.

This paper aims to provide a theoretical explanation of the SER method when applied for planetary gear systems. With the sideband selection of the sun gear fault frequency, together with its harmonics, the SER could be considered as a sum of fault amplitude modulation (AM) indexes. In order to examine the effect of bandwidth selection of the central frequency and the sideband frequency, experimental data under three fault types with rotation speed of 30 Hz are analysed. The results show that the modified SER (denoted by MSER) calculated with a well selected bandwidth is much better than with a single peak point. The schematic of MSER is given in Fig. 1.

The remainder of this paper is organized as follows. In Sect. 2, the SER method will be first interpreted in terms of the sun gear local fault frequency using a reported signal model of a planetary gearbox. The experimental study for validation of the modified SER method is given in Sect. 3. Summary and conclusions are given in Sect. 4.

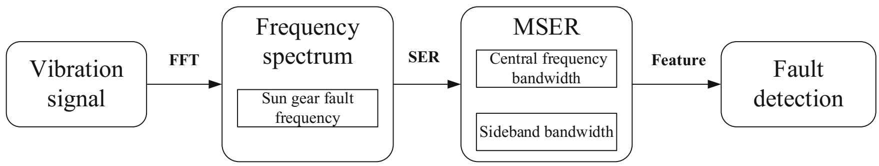


Fig. 1 The schematic of MSER for fault detection

2 Theoretical Analysis of SER

2.1 *Definition of SER*

The reported sideband energy ratio, that is, SER, is defined as the ratio between the sideband peaks and the gear mesh centre frequency peak. First six pairs of sidebands have been used in its calculation for fixed-shaft gearboxes. It has been found to be effective for gear damage detection for fixed-shaft gearboxes. In Eq. 1, SER is expressed as the ratio between the sum of the amplitudes of six sidebands and the amplitude of the centre mesh frequency [4].

$$\mathrm{SER} = \frac{\sum_{i=1}^{6} \mathrm{Sideband\ Ampitude_i}}{\mathrm{Center\ mesh\ frequency\ amplitude}} \tag{1}$$

According to Eq. 1, the SER method sums the amplitudes of the first six sideband peaks on each side of the centre mesh frequency and divides this sum by the amplitude of the central mesh frequency. Before using this method for fault detection of planetary gear system, a theoretical analysis of this SER measure is done using a reported signal model for a planetary gearbox.

2.2 *Signal Model of Sun Gear Local Fault*

When there is a local sun gear fault, according to Feng [2], the vibration of a planetary gearbox consists of both amplitude modulation (AM) and frequency modulation (FM). The sun gear local fault causes modulation of the gear meshing vibration and the frequency of this modulation, in fact, gives the characteristic fault frequency of the sun gear. In addition, the gear meshing frequency will also be modulated by the sun gear rotational speed. As a result, vibration signals to be perceived by a sensor mounted on the gearbox casing can be modeled as [2]:

$$x(t) = \underbrace{[1-\cos(2\pi f_{shaft} t)]}_{AMbyshaftrotation}\underbrace{[1+A\cos(2\pi f_{sun} t+\phi)]}_{AMbysungearfaultfrequency}\cos[2\pi f_{mesh} t+\underbrace{B\sin(2\pi f_{sun} t+\varphi)}_{FMbysungearfaultfrequency}+\theta] \tag{2}$$

Table 1 Characteristic frequencies of a planetary gearbox

Frequency	f_{shaft}	f_{mesh}	f_{sun}	$f_{carrier}$
Expression	n	$\frac{Z_s Z_r}{Z_s + Z_r} * n$	$\frac{N Z_r}{Z_s + Z_r} * n$	$\frac{Z_s}{Z_s + Z_r} * n$

where f_{shaft} is the shaft rotational frequency, f_{sun} is the sun gear fault characteristic frequency, f_{mesh} is the gear meshing frequency, A and B are the modulation coefficients of AM and FM, respectively, and ϕ and φ are the initial phases of AM and FM, respectively. The relationships among the main frequency components of a planetary gearbox are given in Table 1, where $f_{carrier}$ is the carrier rotation frequency, N is the number of equally spaced planet gears, n is the sun gear rotation frequency, Z_s is the number of teeth of the sun gear, and Z_r is the number of teeth of the ring gear tooth.

According to Eq. 2, the fault frequency induced by sun gear fault will directly lead to the following sideband components: $f_{mesh} \pm f_{sun}$. During the engagement of the faulty tooth, the meshing excitation magnitude caused by different severity levels of the fault may be different. The amplitudes of the sidebands $f_{mesh} \pm f_{sun}$ in the frequency spectrum may be an effective fault severity indication. If the data is long enough, we don't believe that the phase factor will influence these amplitudes. We will not consider the FM part either in this paper. Considering the transfer path effect [7, 8] of the signal, the signal model given in Eq. 2 is simplified to the following in Eq. 3.

$$x(t) = A_0(1 - \cos 2\pi f_{shaft} t)[1 + \beta_1 \cos(2\pi f_{sun} t)] \cos(2\pi f_{mesh} t) \tag{3}$$

where A_0 is the AM index of the vibration signal incorporating the transfer path effect, and β_1 is the AM index of the sun gear fault.

Expanding Eq. 3 gives:

$$\begin{aligned} x(t) = {} & A_0 \cos(2\pi f_{mesh} t) - A_0 \cos(2\pi f_{shaft} t) \cos(2\pi f_{mesh} t) \\ & + A_0 \beta_1 \cos(2\pi f_{sun} t) \cos(2\pi f_{mesh} t) \\ & - A_0 \beta_1 \cos(2\pi f_{sun} t) \cos(2\pi f_{shaft} t) \cos(2\pi f_{mesh} t) \end{aligned} \tag{4}$$

Based on Eq. 4, the frequency contents of the resultant frequency spectrum will have $f_{mesh}, f_{mesh} \pm f_{sun}, f_{mesh} \pm f_{shaft}$ and $f_{mesh} \pm f_{shaft} \pm f_{sun}$. Note that for each of the resultant frequencies, the amplitude values depend on the two modulation indexes A_0 and β_1. The sideband components $f_{mesh} \pm f_{sun}$ only come from the part of Eq. 4 marked in a rectangle. This means that β_1 is of great importance for sun gear local fault detection. It will be further discussed below.

The central frequency as well as the sidebands are the key components in the SER method for fixed-shaft gearboxes. We now discuss them for a planetary gearbox. Generally, the vibration induced by a gear fault may be reflected in a series of harmonic sidebands. According to the rectangle marked in Eq. 4 and considering the harmonic AM effects of f_{sun}, the vibration model can be modified as,

$$x(t) = A_0 \left[1 + \sum_{m=-\infty}^{+\infty} \beta_m \cos(2\pi m f_{sun} t) \right] \cos(2\pi f_{mesh} t) \tag{5}$$

For the sidebands of the sun gear fault frequency, according to Eq. 1, we can use Eq. 5 and modify the SER of Eq. 1 to the following,

$$MSER = \frac{\frac{1}{2} A_0 \sum_{m=1}^{6} \beta_m}{\frac{1}{2} A_0} = \sum_{m=1}^{6} \beta_m \tag{6}$$

The modified SER expression given in Eq. 6 establishes a relationship between the central frequency and the sun gear fault induced sidebands, eliminates the effect of A_0, and retains only the local fault sideband amplitudes, namely $\sum_{m=1}^{6} \beta_m$. For detection of the sun gear tooth fault, we can use the modified SER expression given in Eq. 6 under constant rotation speeds.

2.3 Bandwidth Selection

From the theoretical explanation given in Sect. 2.2, the MSER is expected to be a good feature for sun gear fault detection. Actually, another important factor should be noticed that, the bandwidth selection of the sideband and the central frequency is also important. Due to practical fluctuations of the rotation speed, though it is set at a constant value, the energy contained in a bandwidth for MSER application is expected to be better than the instant peak frequency value along. We will conduct bandwidth selection in later data analysis.

3 Experimental Studies

In the following, experimental data were acquired from a lab planetary gearbox test rig. The experimental set-up consisted of a spur gearbox and a one stage planetary gearbox driven by a 2.24 kW three phase electrical motor controlled by a motor speed controller. A vibration accelerometer (with sensitivity of 100 mV/g and frequency range 0–10 kHz) was used for capturing vibration data. Data lasting 4.8 s in time were collected for each controlled condition. The sampling frequency was set to be 10240 Hz. For each sun gear fault scenario, 10 groups of data were collected under the constant sun gear rotational frequency of 30 Hz. The test rig

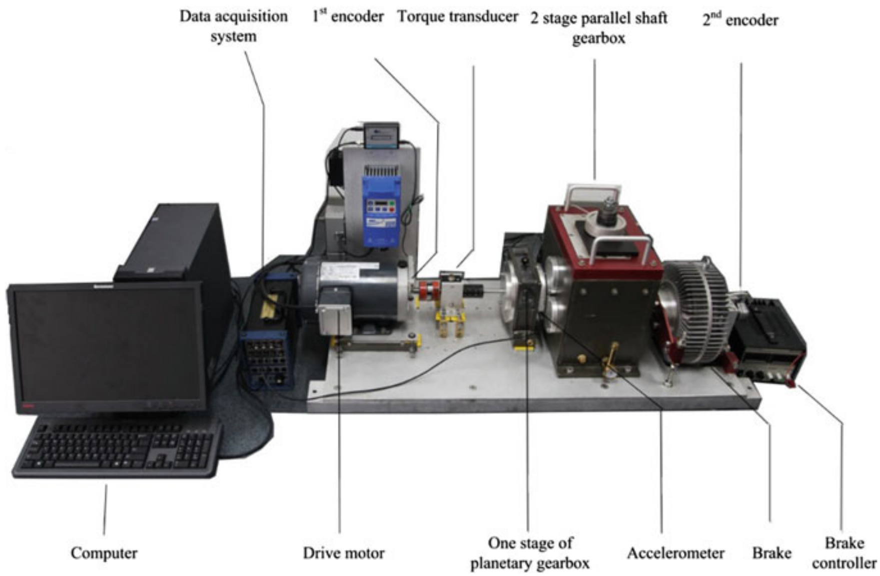


Fig. 2 Planetary gearbox test rig

Table 2 Test rig parameters

Item:	# of teeth (sun gear)	# of teeth (planet gear)	# of teeth (ring gear)	# of planets
Value:	28	36	100	4

configuration is shown in Fig. 2 and the key parameters of the planetary gearbox are listed in Table 2.

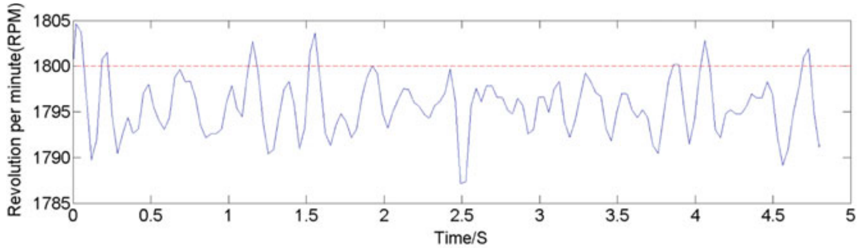
Three different sun gear health scenarios were considered for study. They were the healthy condition, the tooth pitting condition, and the tooth crack condition. Figure 3 illustrates these three health conditions.

(a) Healthy (b) Tooth pitting (c) Tooth crack

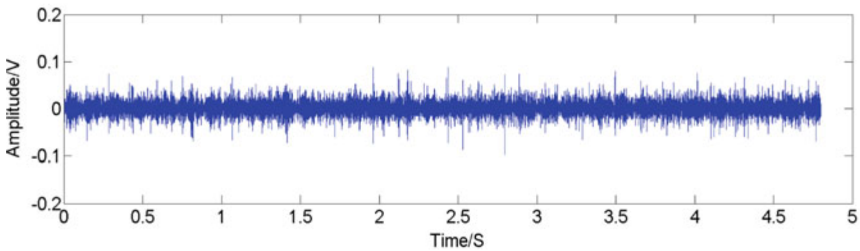
Fig. 3 The three considered health conditions of the sun gear

Take the healthy sun gear scenario when the controlled rotation speed was 30 Hz as an example. We have plotted the measured rotation speed, the time domain vibration data, and the frequency spectrum of the vibration data in Fig. 4. We can see clear variations in the measured rotating speed even the controller speed was set at 30 Hz (or 1800 RPM).

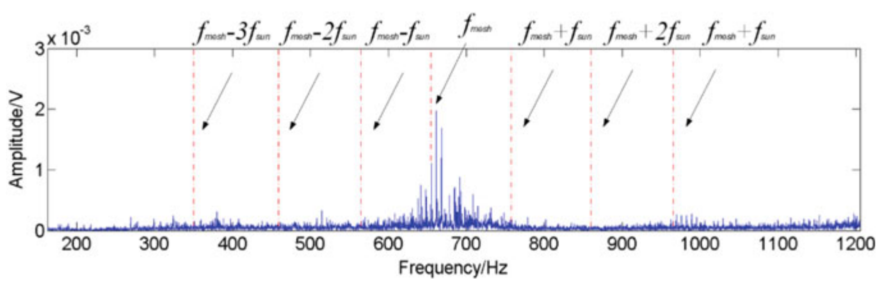
Due to the natural speed fluctuations that exists in the collected data, the bandwidth selected makes a difference in data analysis and fault detection. In Fig. 5, we have plotted the MSER calculated under two different bandwidth treatments, (a) when a bandwidth of 2 Hz was used around the central frequency and (b) when the single frequency identified at the peak amplitude was used. Data



(a) Rotation speed

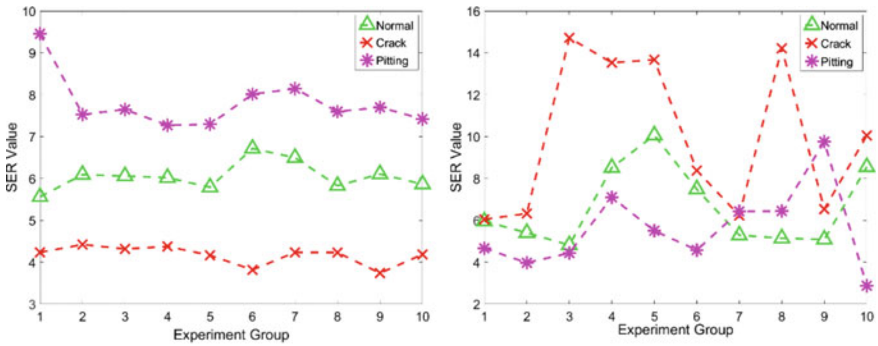


(b) Time domain vibration signal



(c) Frequency spectrum of the vibration data

Fig. 4 Measured rotation speed (**a**), time (**b**), and frequency domain signals (**c**) when the sun gear was healthy and the speed was set at 1800 RPM



(a) MSER calculated with a bandwidth (b) MSER with a single frequency

Fig. 5 Effect of bandwidth selection on MSER when rotation speed = 30 Hz

analysed were collected under a constant rotation speed of 30 Hz. The MSER values under all three health scenarios of the sun gear are presented in Fig. 5.

From Fig. 5, when the rotation speed is 30 Hz, the fault detection ability of MSER with a proper bandwidth setting (2 Hz) is much better than the MSER calculated with a single frequency at the peak. It can be seen that all three health scenarios are clearly separated in the plotted MSER value trends in Fig. 5(a). However, in Fig. 5(b), the three health scenarios are mixed together and thus are difficult to detect with the SER trend.

4 Summary and Conclusion

The original SER method, which has been proved effective for fixed-shaft gearboxes, is studied and modified in this paper. For planetary gearboxes, the modified SER indicator called MSER is developed utilizing a reported signal model of planetary gearbox signals. Added by the proper sideband selection, the proposed MSER is demonstrated to be an effective indicator of sun gear health condition. Future research includes consideration of other faults in planetary gearboxes and dynamic operating speed conditions.

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