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Research on Instantaneous Angular Speed Signal Separation Method for Planetary Gear Fault Diagnosis

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Abstract

Planetary gear train is a critical transmission component in large equipment such as helicopters and wind turbines. Conducting damage perception of planetary gear trains is of great significance for the safe operation of equipment. Existing methods for damage perception of planetary gear trains mainly rely on linear vibration analysis. However, these methods based on linear vibration signal analysis face challenges such as rich vibration sources, complex signal coupling and modulation mechanisms, significant influence of transmission paths, and difficulties in separating damage information. This paper proposes a method for separating instantaneous angular speed (IAS) signals for planetary gear fault diagnosis. Firstly, this method obtains encoder pulse signals through a built-in encoder. Based on this, it calculates the IAS signals using the Hilbert transform, and obtains the time-domain synchronous average signal of the IAS of the planetary gear through time-domain synchronous averaging technology, thus realizing the fault diagnosis of the planetary gear train. Experimental results validate the effectiveness of the calculated IAS signals, demonstrating that the time-domain synchronous averaging technology can highlight impact characteristics, effectively separate and extract fault impacts, greatly reduce the testing cost of experiments, and provide an effective tool for the fault diagnosis of planetary gear trains.

Keywords

Planetary Gear Train, Encoder Signal, Instantaneous Angular Speed Signal, Time-Domain Synchronous Averaging, Fault Diagnosis

1. Introduction

Planetary gearboxes are characterized by their small size, high transmission ratio, and high efficiency, and are widely used in transportation, mining and metallurgy, wind power generation, and other fields. In practical operation, as a key component for transmitting torque, they are subjected to complex dynamic overload forces. The gears are prone to failure, and once a failure occurs, it can lead to serious consequences, even causing injuries or fatalities. Therefore, it is of great significance to conduct research on planetary gear systems.

Damage perception of transmission components is mainly based on the analysis of linear vibration signals. Various signal processing methods have been applied to extract gear fault characteristics, including time-frequency analysis [1], wavelet transform [2], empirical mode decomposition [3], signal sparse decomposition [4], and others. However, compared to other transmission components, conducting damage perception of planetary gear trains based on vibration signal analysis is more challenging. Due to the unique motion characteristics of planetary gear trains, even in a healthy state, theoretically, planetary gear trains will produce fault characteristic frequency components. For example, the fault characteristic frequency of the ring gear is equal to the frequency at which the planetary gear passes through the ring gear, naturally also equal to the frequency at which the planetary gear train passes through the sensor; similarly, the fault characteristic frequency of the sun gear is equal to the frequency at which the planetary gear passes through the sun gear; and regardless of whether there is damage to the planetary gear train, the frequency components of the planetary gear passing through the sun gear or ring gear always exist.

Considering that tooth damage leads to a decrease in meshing stiffness and transmission smoothness, which is the fundamental physical basis for perceiving gear damage, compared to traditional linear vibration signals, the response of instantaneous speed to changes in transmission smoothness is more direct and sensitive. Moreover, the torsional vibration signal obtained based on speed measurement is not affected by transmission paths, is not affected by multi-interface energy dissipation and multi-path signal superposition attenuation, and is less affected by high-frequency vibration components. In addition, the speed signal is the physical quantity that the state perception system needs to measure. Using the speed signal instead of the vibration signal not only is expected to obtain more effective approaches for state monitoring and fault prediction but also can reduce the hardware and testing costs of perception systems.

In recent years, a large number of scholars at home and abroad have conducted extensive research on encoder signals. Bourdon *et al.* [5] proposed a filter defined in the angular frequency domain, through which the detection of the filter can quantify the magnitude of angular velocity changes related to faults in the outer race of bearings. Liu *et al.* [6] derived a method for solving the time-varying meshing stiffness when tooth root crack faults occur based on the energy method, and established the corresponding dynamic model to extract the torsional vibration contained in the encoder response signal under crack damage conditions. Feng *et al.* [7] proposed extracting gear fault features from the ratio spectrum of the reciprocal of the resampled time intervals at equal angles, overcoming the difficulties of fault diagnosis under variable speeds. It is noted in the research that the encoder signal at low speeds not only contains the interested fault components but also contains same-order components caused by factors such as manufacturing or installation errors. These two components are usually mixed together, making it difficult to extract fault characteristics. Guo *et al.* [8] proposed a feature extraction and detection method based on the relative value of fault characteristic indicators to address the difficulty of extracting fault characteristic orders in encoder signals due to sun gear tooth root crack faults at low speeds.

The analysis methods mentioned above for encoder signals mostly achieve final fault diagnosis based on fault characteristic frequencies. However, due to the unique motion characteristics of planetary gear trains, their fault characteristic signals are often overwhelmed by other components, resulting in unclear fault characteristics and difficulty in achieving good results.

The time-domain synchronous averaging analysis method is an effective method for analyzing time-domain features of signals. By superimposing and averaging signals of interest over a certain period, it can reduce the influence of background noise and other components, and enhance the representation of vibration characteristics related to the target gear in the signal. McFadden [9] obtained meshing vibration signals of individual planetary gears through windowed time-domain synchronous averaging analysis, while Smidt [10] installed sensors on the planetary frame and monitored the gearbox's condition through time-domain synchronous averaging analysis. Yip [11] preprocessed vibration signals using the time-domain synchronous averaging method and then extracted feature indicators from the preprocessed results to achieve gearbox fault diagnosis. Abboud [12] proposed a generalized time-domain synchronous averaging algorithm that can be applied under variable speed and load conditions.

This paper addresses the challenging issues faced by planetary gear systems, such as abundant sources of vibration, complex signal coupling and modulation mechanisms, significant influences from transmission paths, and difficulties in damage information separation. It proposes a method for fault diagnosis of planetary gears through the separation of instantaneous angular speed signals. This method can diagnose faults in planetary gear systems and assess the severity of the faults, providing strong support for the life prediction and operation and maintenance of planetary gear systems. Firstly, encoder pulse signals are obtained through a built-in encoder. Based on this, the IAS signals are calculated using the Hilbert transform. Then, the time-domain synchronous averaging technology is applied to obtain the time-domain synchronous average signal of the IAS of the planetary gear, thus achieving the fault diagnosis of the planetary gear train. Experimental results validate the effectiveness of the calculated IAS signals, demonstrating that the time-domain synchronous averaging technology can highlight impact characteristics, effectively separate and extract fault impacts, greatly reduce the testing cost of experiments, and provide an effective tool for the fault diagnosis of planetary gear trains.

2. Method for Acquiring Instantaneous Angular Velocity

In the operation of a planetary gearbox, angular displacement represents the change in speed and depends on two components: the average speed and the fluctuation component.

$$\theta=\left(\bar{\varpi}\pm\omega\right)t \tag{1}$$

Optical encoders are commonly used to obtain angular displacement. Due to the variation in rotor speed, the pulse sequence generated by the encoder also changes. Therefore, the angular velocity can be calculated by the time interval, thus allowing the calculation of angular displacement.

Due to the presence of a varying component in angular velocity, the measured pulse sequence is a phase-modulated signal. Assuming that this modulated signal is bandpass-filtered, only the content around the fundamental frequency or its harmonics is retained. Therefore, the bandpass signal can be represented as:

$$s\left(t\right)=A_c\cos\left(\omega_c t+\phi_c\right)+\sum_i\beta_i\sin\left(\omega_i t+\phi_i\right) \tag{2}$$

Where $\sum_i\beta_i\sin\left(\omega_i t+\phi_i\right)$ represents the modulating signal with a period, and the subscript c represents the carrier signal.

Neglecting the initial phase ϕ_c and representing the phase variation of the summation term in equation (2) as $\phi\left(t\right)$, the modulating signal can be simplified as:

$$s\left(t\right)=A_c\cos\left[w_c t+\phi\left(t\right)\right] \tag{3}$$

The relationship between constant speed and carrier frequency is:

$$\bar{\varpi}=\frac{\omega_c}{n} \tag{4}$$

Where n is the number of pulses per revolution (PPR), defined by the encoder model. Similarly, the variation in angular velocity can also be expressed as:

$$\omega\left(t\right)=\frac{\mathrm{d}\phi\left(t\right)}{\mathrm{d}t} \tag{5}$$

The carrier frequency of the signal can be calculated through Fourier transform. However, demodulation techniques must be used to obtain changes in angle and thus obtain the IAS signal.

In signal processing, a signal that lacks negative frequency components is referred to as an analytic signal. The analytic representation is the complex form of the actual measured modulated signal. Therefore, the analytical form, denoted as $s(t)$, is represented as the real part, with its Hilbert transform represented as the imaginary part.

$$s_a\left(t\right)=s\left(t\right)+jH\left[s\left(t\right)\right]=A_c\mathrm{e}^{j\left[\omega ct+\phi\left(t\right)\right]} \tag{6}$$

The Hilbert transform of $s(t)$ is:

$$H\left[s(t)\right]=A_c\sin\left[\omega_c t+\phi(t)\right] \tag{7}$$

To obtain the signal of angle variation, the carrier frequency component in equation (6) is first eliminated by multiplying with the complex signal $\mathrm{e}^{-jw_c t}$.

$$\mathrm{e}^{j\phi(t)}=\mathrm{e}^{j\left[\omega ct+\phi(t)\right]}\mathrm{e}^{-j\omega ct} \tag{8}$$

IAS signal is

$$\phi(t)=\tan^{-1}\frac{\mathrm{Imag}\left[\mathrm{e}^{j\phi(t)}\right]}{\mathrm{Real}\left[\mathrm{e}^{j\phi(t)}\right]} \tag{9}$$

Finally, by taking the time derivative of, the signal of velocity variation or IAS can be obtained.

3. Time-Domain Synchronous Averaging Technique

The time-domain synchronous averaging technique is a common signal processing method, which mainly includes three steps: data segmentation, re-sampling, and averaging processing. In the application to gears, the purpose is to enhance the representation of vibration characteristics related to the target gear in the signal, while reducing the influence of background noise and other components, and extracting specific periodic signals of interest. The specific working principle is shown in **Figure 1**.

In the time-domain synchronous averaging technique, the vibration signal $x(t)$ is first segmented based on the speed pulse signal to obtain the vibration signal for each revolution cycle. Due to variations in operating conditions, environmental factors, etc., the number of data points in each revolution cycle of the vibration signal may vary. Therefore, each segment of data needs to be resampled before averaging to obtain the time-domain synchronous average signal. This process can be represented as:

$$x_{TSA}(t)=\frac{1}{N}\sum_{i=1}^{N-1}x\left(t+iLT_s\right) \tag{10}$$

Where $x_{TSA}(t)$ is the time-domain synchronous average signal, N is the number of averages, L is the number of sampling points in each revolution cycle, T_s is the sampling interval, and the period of the vibration signal $x(t)$ is $T_0 = LT_s$.

If the signal $x(t)$ is composed of a periodic signal $y(t)$ with period T_0 and a white noise signal $n(t)$, then the signal $x(t)$ can be represented as:

$$x(t)=y(t)+n(t) \tag{11}$$

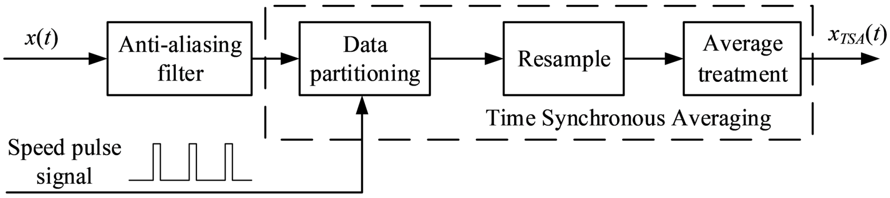


Figure 1. Time domain synchronous averaging schematic.

Dividing the signal $x(t)$ into N segments according to the period T_0 of the signal $y(t)$ and taking the average of the corresponding points in each segment, we obtain:

$$x_{TSA}(t) = y(t) + \frac{1}{\sqrt{N}} n(t) \tag{12}$$

The averaging process exploits the uncorrelated nature of white noise. At this point, the output noise is from the original signal $x(t)$, and the signal-to-noise ratio is improved.

4. Method for Separating Instantaneous Angular Velocity Signals for Planetary Gear Fault Diagnosis

The flowchart of the method for separating instantaneous angular speed signals for planetary gear fault diagnosis is shown in **Figure 2**, which includes two steps: obtaining instantaneous angular velocity and obtaining time-domain synchronous average signals.

4.1. Obtaining Instantaneous Angular Speed Signals

1) Perform Fourier transform on the real signal $s(t)$ to transfer the signal to the frequency domain. Calculate the amplitude spectrum based on the FFT result, and

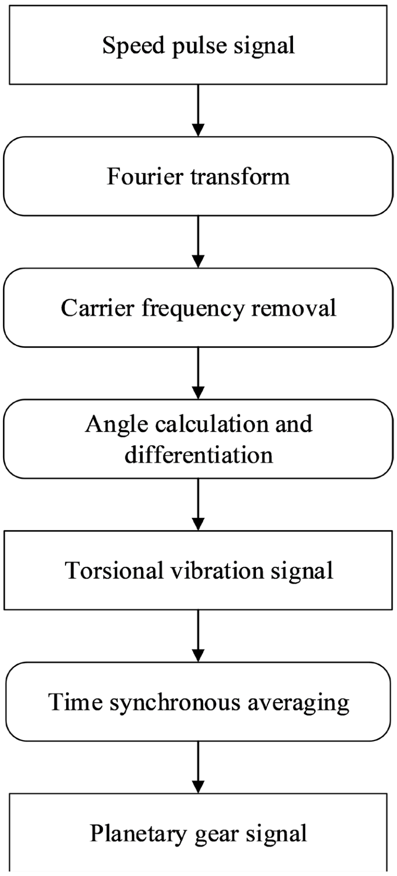


Figure 2. Methodology flow chart.

find the position corresponding to the carrier frequency in the amplitude spectrum, which is equal to the pulse count multiplied by the rotor speed.

2) Set the FFT results within the negative frequency range to zero. This achieves the real analytic representation required by equation (7). Maintain the FFT results around the carrier frequency, setting all other results in the positive frequency range to zero. Shift the filtering to the right side of the carrier frequency to the beginning of the positive frequency range, and shift the filtering on the left side of the carrier frequency to the negative frequency range of the filtering window. This result is the angle variation signal obtained by equation (9), which removes the influence of the carrier frequency.

3) By taking the time derivative of the angular displacement, the signal of velocity variation or IAS can be obtained.

4.2. Obtaining Time-Domain Synchronous Average Signals

Based on the encoder pulse signal, the IAS signal is segmented to obtain a signal within one revolution cycle. Each segment of data is resampled, and then the number of sampling points for each gear meshing is determined based on the number of teeth on the ring gear. This process is repeated for one revolution of the planetary gear, and finally, averaging is performed to obtain the time-domain synchronous average signal.

5. Experimental Signal Verification

To validate the effectiveness of the method, a test bench for simulating planetary gear faults was constructed as shown in **Figure 3**. The test bench consists of a variable frequency motor, a torque and speed sensor, a planetary gearbox, an encoder, a radial loader, a loading device, and a coupling. The test system used consists of vibration acceleration sensors, photoelectric encoders, acquisition cards, and data conditioning modules. The sensitivity of the vibration acceleration sensor is 10.02 mV/ms^{-2} and is installed at the top and horizontal ends of the planetary gearbox. The photoelectric encoder used generates 1024 speed pulses per revolution. The parameters of the planetary gearbox are shown in **Table 1**. The structure of the planetary gear system and a broken tooth fault on a planetary gear are shown in **Figure 4**.

During the experiment, the speed was set to 600 rpm, with a sampling frequency of 51.2 kHz and a sampling time of 180 s, for both the healthy and faulty states of the planetary gear. The local encoder pulse signals for the healthy and faulty states of the planetary gear are shown in **Figure 5** and **Figure 6**. When a gear fault exists, amplitude modulation occurs due to load fluctuations, and frequency modulation occurs due to speed fluctuations, leading to changes in the fault characteristic frequencies. The characteristic frequencies of the planetary gearbox were calculated based on the actual measured speed signals and are shown in **Table 2** and **Table 3**.

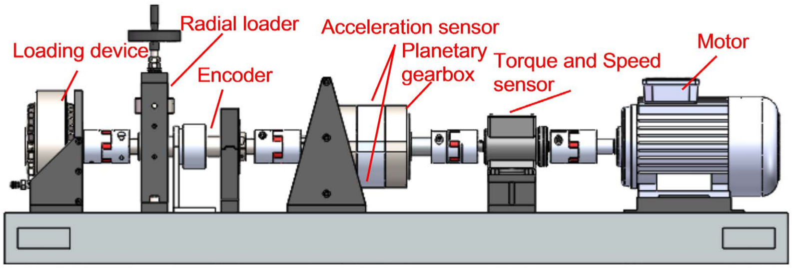


Figure 3. Planetary gear train failure simulation test bench.

Table 1. Parameters of planetary gearbox.

Gear	Sun	Planet	Ring
Number of teeth	21	31 (3)	84

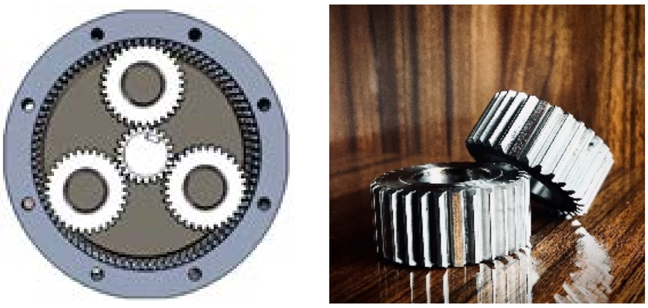

(a) Planetary gearbox (b) Faulty planetary gear

Figure 4. Planetary gearbox and broken tooth planetary gear.

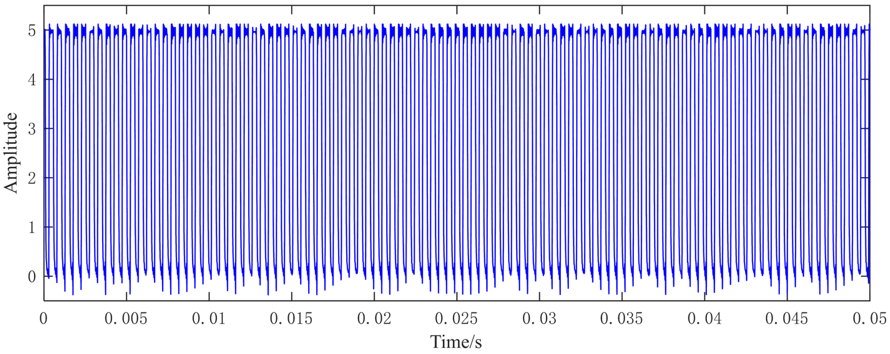


Figure 5. Local encoder pulse signal under health state.

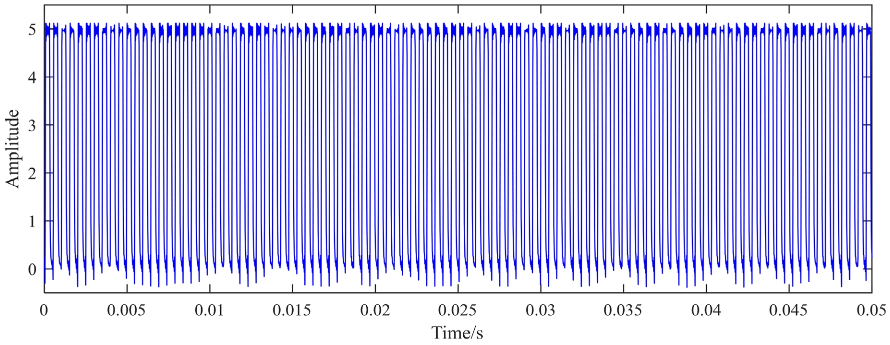


Figure 6. Local encoder pulse signal in fault state.

Table 2. Characteristic frequency of planetary gearbox in health state.

Meshing frequency	Rotating frequency		Characteristic frequency		
	Sun gear	Planetary carrier	Ring gear	Planetary gear	Sun gear
167.366 Hz	9.9629 Hz	1.9926 Hz	3.9852 Hz	5.3992 Hz	7.9703 Hz

Table 3. Characteristic frequency of planetary gearbox in fault state.

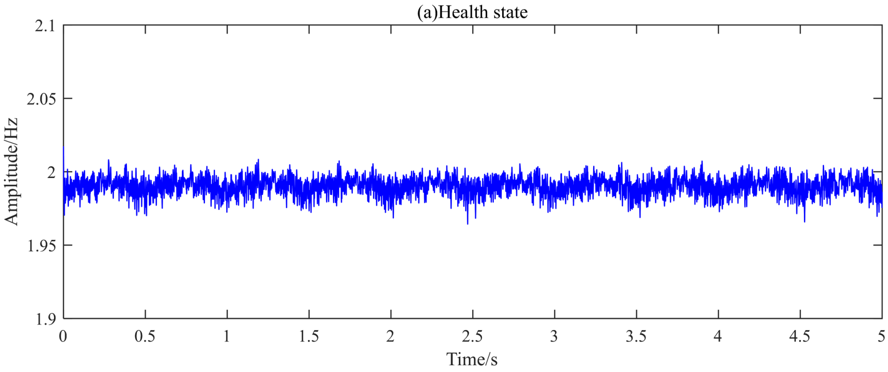
Meshing frequency	Rotating frequency		Characteristic frequency		
	Sun gear	Planetary carrier	Ring gear	Planetary gear	Sun gear
166.9582 Hz	9.9380 Hz	1.9876 Hz	3.9752 Hz	5.3857 Hz	7.9504 Hz

Analyzing the encoder pulse signals for the normal and faulty states of the planetary gear, the IAS signals were obtained using the Hilbert transform based on the calculated carrier frequency ($f_c{*}PPR$). **Figure 7** shows the IAS signals for both states within 1 second. It is evident that the signal fluctuation is greater in the faulty state compared to the healthy state.

To better reflect the fault characteristics and validate the effectiveness of the signals, fast Fourier transforms (FFT) were performed on the signals for both states. **Figure 8** shows the spectra near the first meshing frequency for both states. It is evident from the figure that there are prominent peaks at frequencies around $f_m \pm nf_p \pm kf_c$ ($f_m - 2f_p$, $f_m - f_p$, $f_m + f_c - f_p$, $f_m - f_c + f_p$, $f_m + f_p$, $f_m + 2f_p$). These peaks have at least twice the amplitude compared to the normal signal, and they are related to the local fault characteristic frequency fp of the planetary gear. This indicates that a fault has occurred in the planetary gear. A local fault in the planetary gear will cause an uneven distribution of loads on the planetary frame. This uneven load distribution enhances the modulation effect of the planetary frame's rotational motion on the meshing vibration, resulting in peaks at frequencies around $f_m \pm kf_c$ ($f_m - 2f_c$, $f_m - f_c$, $f_m + f_c$, $f_m + 2f_c$) being greater than those in the normal signal. In conclusion, this demonstrates the effectiveness of the calculated IAS signal.

To further highlight the impact features and clearly observe the state of each gear tooth, the IAS signal was segmented based on the encoder pulse signal to obtain a signal within one revolution cycle. Each segment of data was resampled, and then the number of sampling points for each gear meshing was determined based on the number of teeth on the ring gear. This process was repeated for one revolution of the planetary gear, and finally, averaging was performed to obtain the time-domain synchronous average signal.

After processing the IAS signal as described above, it was found that each gear meshing had 306 sampling points. The synchronous averaging results are shown in **Figure 9**. It is clear that the signal for each gear meshing cycle is very stable in the normal state of the planetary gear. However, for the faulty state of the planetary gear, it can be clearly seen that the impact amplitude of the 21st gear meshing is significantly larger than that of the other gear meshings. It can be inferred that there is a fault in the 21st gear of the planetary gear. Experimental signal verification has shown that this method has good diagnostic effectiveness for planetary gear faults.


(a)Health state

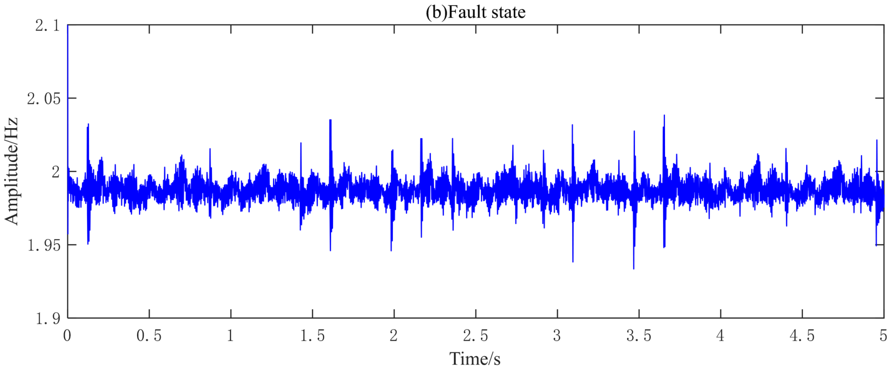

(b)Fault state

Figure 7. IAS signal.

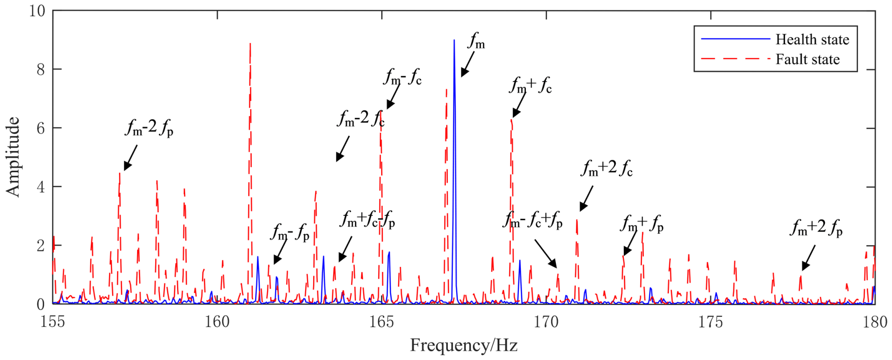
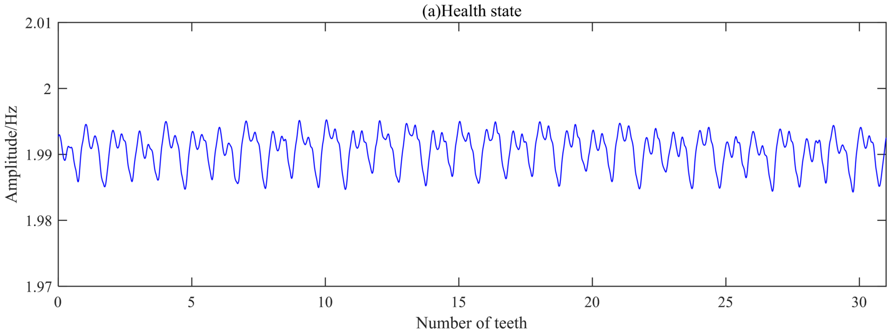


Figure 8. IAS signal spectrum diagram.


(a)Health state

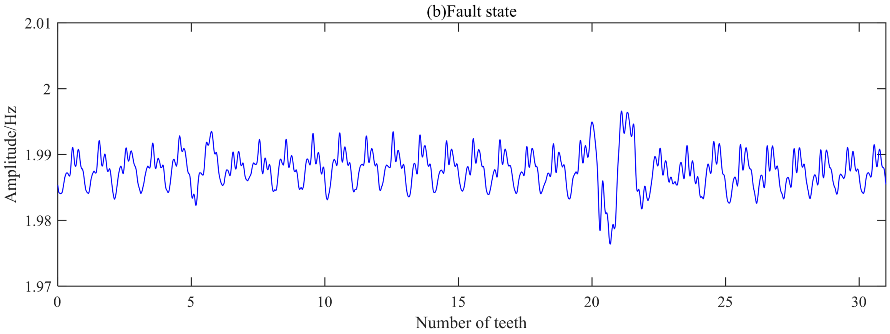


Figure 9. TSA signal.

6. Conclusions

This paper proposes an instantaneous angular speed signal separation method for diagnosing planetary gear faults, addressing the complex modulation characteristics of planetary gear vibration signals and the difficulty in separating fault information. The main conclusions are as follows:

1) By using the IAS signal calculated from the encoder signal and replacing the vibration signal with the speed signal, it is found that the IAS signal reacts more directly and sensitively to changes in transmission smoothness, making fault diagnosis of planetary gearboxes more effective. It also avoids the need for testing multiple vibration signals, significantly reducing the cost of experiments.

2) The time-domain synchronous averaging technique can highlight the impact features of the planetary gear signal, providing a more obvious and intuitive effect for fault identification in planetary gearboxes.

Although this study has achieved phased research results, the following work needs further exploration:

1) The research on the signal separation method in this paper only separates the signal of the planetary gear in the fault state. Further improvement is needed for the separation method of the sun gear and ring gear signals.

2) When the sun gear or ring gear has a fault, the separation of the signals of the planetary gear, sun gear, and ring gear has not been considered. Further research is needed in future studies.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Lei, Y., Kong, D., Li, N. and Lin, J. (2014) Adaptive Ensemble Empirical Mode Decomposition and Its Application to Fault Detection of Planetary Gearboxes. *Journal of Mechanical Engineering*, **50**, 64. https://doi.org/10.3901/JME.2014.03.064

[2] Feng, Z.P. and Qin, S.F. (2016) Planetary Gearbox Fault Diagnosis Based on Hilbert Vibration Decomposition and Higher Order Differential Energy Operator. *Journal of Vibration and Shock*, **35**, 47-54.

[3] Zhu, W. and Feng, Z. (2016) Fault Diagnosis of Planetary Gearbox Based on Improved Empirical Wavelet Transform. *Chinese Journal of Scientific Instrument*, **37**, 2193-2201.

[4] Feng, Z. and Liang, M. (2016) Complex Signal Analysis for Planetary Gearbox Fault Diagnosis via Shift Invariant Dictionary Learning. *Measurement*, **90**, 382-395. https://doi.org/10.1016/j.measurement.2016.04.078

[5] Bourdon, A., Chesné, S., André, H. and Rémond, D. (2019) Reconstruction of Angular Speed Variations in the Angular Domain to Diagnose and Quantify Taper Roller Bearing Outer Race Fault. *Mechanical Systems and Signal Processing*, **120**, 1-15. https://doi.org/10.1016/j.ymssp.2018.09.040

[6] Liu, Z., Kong, D., Zhao, M. and Ma, Z. (2020) Encoder Signal Response Characteristics of Planetary Gear Sets with Cracks. *Journal of Xi' an Jiaotong University*, No. 2, 43-50.

[7] Feng, Z., Gao, A., Li, K. and Ma, H. (2021) Planetary Gearbox Fault Diagnosis via Rotary Encoder Signal Analysis. *Mechanical Systems and Signal Processing*, **149**, 107325. https://doi.org/10.1016/j.ymssp.2020.107325

[8] Li, Z., Guo, Y., Yin, X. And Hua, J. (2023) Encoder Signal Feature Extraction of Sun Gear Fault at Low Speed Using Relative Ratio of Fault Feature lndex. *Mechanical Science and Technology for Aerospace Engineering*, No. 7, 1044-1049.

[9] Mcfadden, P.D. (1991) A Technique for Calculating the Time Domain Averages of the Vibration of the Individual Planet Gears and the Sun Gear in an Epicyclic Gearbox. *Journal of Sound & Vibration*, **144**, 163-172. https://doi.org/10.1016/0022-460X(91)90739-7

[10] Smidt, M.R.D. (2010) Internal Vibration Monitoring of a Planetary Gearbox. Ring Gear.

[11] Yip, L. (2011) Analysis and Modeling of Planetary Gearbox Vibration Data for Early Fault Detection. Doctoral Dissertation, University of Toronto, Canada.

[12] Abboud, D., Antoni, J., Sieg-Zieba, S. and Eltabach, M. (2016) Deterministic-Random Separation in Nonstationary Regime. *Journal of Sound & Vibration*, **362**, 305-326. https://doi.org/10.1016/j.jsv.2015.09.029