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# Vibration signal models for fault diagnosis of planet bearings

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ABSTRACT

Rolling element bearings are key components of planetary gearboxes. Among them, the motion of planet bearings is very complex, encompassing spinning and revolution. Therefore, planet bearing vibrations are highly intricate and their fault characteristics are completely different from those of fixed-axis case, making planet bearing fault diagnosis a difficult topic. In order to address this issue, we derive the explicit equations for calculating the characteristic frequency of outer race, rolling element and inner race fault, considering the complex motion of planet bearings. We also develop the planet bearing vibration signal model for each fault case, considering the modulation effects of load zone passing, time-varying angle between the gear pair mesh and fault induced impact force, as well as the time-varying vibration transfer path. Based on the developed signal models, we derive the explicit equations of Fourier spectrum in each fault case, and summarize the vibration spectral characteristics respectively. The theoretical derivations are illustrated by numerical simulation, and further validated experimentally and all the three fault cases (i.e. outer race, rolling element and inner race localized fault) are diagnosed.

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## 1 Introduction

Planetary gearboxes have unique merits such as compact structure, large transmission ratio, high load-bearing capacity, smooth operation, and coaxial shafting. Therefore, they are widely used in wind turbines, helicopters, heavy trucks, etc. Once fault occurs in planetary gearboxes, it will reduce transmission efficiency of the power train, or even lead to shut-down of the entire machinery. Hence, planetary gearbox fault diagnosis has been an important topic and is attracting more and more attention.

Researchers have made important contributions to planetary gearbox fault diagnosis [1,2]. In order to thoroughly understand the vibration mechanism and characteristics of planetary gearbox faults, Chaari et al. [3,4], Inalpolat and Kahraman [5,6], and Mark [7,8] respectively investigated the effects of gear fault, manufacturing errors and loading on the vibration responses through dynamics modeling and analysis. Their works provide a theoretical guide to correlate vibration signatures with gear faults. Lei et al. [9] and Bartelmus and Zimroz [10,11] respectively proposed statistical indices for condition monitoring of planetary gearboxes under constant and nonstationary operations. In order to extract fault signatures from vibration signals, McFadden [12,13] studied the spectral characteristics of planetary gearbox vibration signals,

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and generalized the time domain averaging method. Samuel and Pines [14,15] proposed a vibration separation method for planet and sun gears, and a constrained adaptive wavelet lifting method to analyze individual tooth mesh waveforms. Barszcza and Randall [16] applied the spectral kurtosis method to detect a planetary gearbox tooth crack. Lei et al. [17] improved the adaptive stochastic resonance method and applied it to extract the weak fault symptoms of a planetary gearbox. Feng et al [18–24] summarized the spectral characteristics of planetary gearbox vibration signals, presented amplitude and frequency demodulation analysis methods for fault diagnosis under constant operations, and further proposed to extract the time-varying fault signatures under nonstationary conditions via time–frequency analysis.

However, most of the above reported work focuses on the sun, the planet and the ring (annular) gears, while few literature concerns bearings in planetary gearboxes. Rolling element bearings are key components of planetary gearboxes. For planetary gearboxes, the ring gear is usually fixed, and the sun gear and planet carrier connect to the input and output shaft respectively and rotate. Inside the gearbox, the planet gears mesh simultaneously with the sun and ring gears, and their motion is highly complicated, including spinning around the planet pin and revolution with the planet carrier about the sun and ring center. To allow free rotation and enable efficient power transmission, rolling element bearings are commonly used to support the sun and planet gears, as well as the planet carrier. Obviously, bearing fault will result in deficiency in power transmission or even failure of gearboxes. Therefore, bearing fault diagnosis plays an important role in planetary gearbox diagnostics.

For the bearings supporting the sun gear and planet carrier, they are usually fixed on the bearing housings which are connected to the gearbox casing. They work in the same way as fixed-axis bearings commonly used in many applications, and their vibration signals also have similar characteristics, thus can be diagnosed using traditional analysis method such as envelope spectrum [25–27]. However, for the bearings supporting the planet gears and connecting them to the planet carrier through planet pins, they not only spin with the planet gear around the planet pin fixed to the planet carrier, but also revolve with the planet carrier about the sun and ring gear center. Because of the highly complex motion of planet bearings, their vibration signals are very intricate, thus making planet bearing fault diagnosis a difficult task.

To date, very few papers concern planet bearing fault diagnosis. Jain and Hunt [28,29] considered the ring gear deformation and a planet bearing defect, developed a dynamics model of a planetary gearbox, and analyzed the spectral characteristics of vibration response. Bonnardot et al. [30] proposed a signal denoising method based on angle domain resampling, to analyze the vibration signal of a planetary gearbox with a faulty planet bearing. Fan and Li [31] used internal sensor on the planet carrier to avoid the modulation effect due to time-varying vibration transmission path, and proposed a hybrid approach based on cepstrum whitening, minimum entropy deconvolution, spectral kurtosis and squared envelope analysis for planet bearing diagnostics. These works made important contributions to planet bearing fault diagnosis.

Nevertheless, planet bearing kinetics is very complicated, involving not only spinning around the planet pin but also revolving with the planet carrier about the sun and ring gear center. Under such a complicated motion mechanism, the fault characteristic frequency of each bearing component (inner and outer race, cage and rolling element) is totally different from the common fixed-axis case. Therefore, the equations for calculating planet bearing fault characteristic frequency need to be carefully investigated and derived. More importantly, in addition to the load zone passing effect, the revolution and spinning lead to extra complex effects on the planet bearing vibration, such as the amplitude modulation (AM) due to the time-varying vibration transfer path from the fault point to sensors, and the AMs caused by variation in the angle between the planet-ring gear pair mesh line of action and the fault induced impact force vector and by variation in the angle between the planet-sun gear pair mesh line of action and the fault induced impact force vector (in the cases of outer race and rolling element fault). Hence, their vibration signals are rather intricate, and need further investigation on the signal model, for thoroughly understanding and revealing the spectral characteristics of planet bearing fault induced vibrations.

This paper aims to address the above issues associated with planet bearing fault diagnosis. We derive the explicit equations for calculating planet bearing component fault characteristic frequencies. We also develop the amplitude modulation and frequency modulation (AM–FM) signal models for the case of outer race, rolling element and inner race fault respectively, considering the unique features of planet bearing motion and the consequent modulation effects, and summarize the spectral characteristics. Hereafter, the paper is organized as follows. Section 2 develops the AM–FM signal models for each bearing component fault case. Section 3 derives the exlicit equations for calculating planet bearing fault characteristic frequencies. Section 4 derives the explicit equations of Fourier spectrum of each bearing component fault case, and summarizes the corresponding spectral characteristics. Sections 5 and 6 validate the theoretical derivations using numerically simulated signals and lab experimental datasets of a planetary gearbox. Section 7 draws conclusions.

## 2 Vibration signal model

In this section, we firstly model the vibration signal generated at the bearing component localized fault point as an AM–FM process. Then, we consider the effects of load zone passing, and time-varying angle between the planet-ring mesh and planet-sun mesh and the fault induced impact force vector due to bearing spinning, as well as the effect of time-varying vibration transfer path from the fault point to the sensor location due to bearing revolution with the planet carrier, thereby developing the sensor perceived vibration signal models for outer race, rolling element and inner race fault cases respectively.

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