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A phase angle based diagnostic scheme to planetary gear faults diagnostics under non-stationary operational conditions

Ke Feng [a], Kesheng Wang [a,*], Qing Ni [a], Ming J. Zuo [a,b], Dongdong Wei [a]

[a] Equipment Reliability, Prognostics and Health Management Lab (ERPHM) School of Mechatronics Engineering, University of Electronic Science and Technology of China, Chengdu 611731, PR China
[b] Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, Canada T6G 1H9

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ABSTRACT

Planetary gearbox is a critical component for rotating machinery. It is widely used in wind turbines, aerospace and transmission systems in heavy industry. Thus, it is important to monitor planetary gearboxes, especially for fault diagnostics, during its operational conditions. However, in practice, operational conditions of planetary gearbox are often characterized by variations of rotational speeds and loads, which may bring difficulties for fault diagnosis through the measured vibrations. In this paper, phase angle data extracted from measured planetary gearbox vibrations is used for fault detection under non-stationary operational conditions. Together with sample entropy, fault diagnosis on planetary gearbox is implemented. The proposed scheme is explained and demonstrated in both simulation and experimental studies. The scheme proves to be effective and features advantages on fault diagnosis of planetary gearboxes under non-stationary operational conditions.

1. Introduction

Planetary gearboxes are widely used due to their unique features such as small size, lightweight and large transmission ratio. It is commonly recognized as a key transmission component to many engineering systems. However, due to its tough working environments, for example in wind turbines and helicopters, fluctuating loads as well as varying rotational speeds are inevitable. Gears, shafts and bearings in planetary gearboxes, therefore, tend to subject to failures and their failures may cause unexpected economic loss. Condition monitoring of planetary gearboxes under non-stationary operational conditions therefore becomes a key method to ensure the reliability of the whole system.

Compared with a fixed-axis gear system, even at constant rotational speed, the measured vibration from a planetary gearbox is very complex due to its unique physical structure and dynamic motions of internal gears [1]. It may bring tremendous difficulties in fault diagnosis to planetary gearboxes. In recent years, researchers have done a plenty of works on fault diagnostics to planetary gearbox systems via vibration based methods. McFadden [2,3] proposed a time domain averaging method for planetary gearbox fault diagnostics. Lei [4] introduced two diagnostic parameters (FRMS and NSDS) for fault detection of planetary gearboxes. McNames [5] applied Fourier series analysis to study the vibration signal and found that the vibration signal spectrum is typically asymmetric. Feng [6] deduced the explicit equations for calculating the

* Corresponding author.
E-mail address: keshengwang@uestc.edu.cn (K. Wang).

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Nomenclature

Roman symbols

f_r	characteristic frequency of faulty ring gear
f_p	characteristic frequency of faulty planet gear
f_s	characteristic frequency of faulty sun gear
f_{sr}	rotating frequency of sun gear
f_c	rotating frequency of the carrier
f_m	gear meshing frequency
f_{sh}	rotating shaft frequency of the shaft with the damaged gear
f_{ch}	characteristic frequency
f_{rt}	rotating frequency
O_n	order of rotational frequency of sun gear
O_s	order of the characteristic frequency of the faulty sun gear
O_m	order of gear meshing frequency
A,C	amplitude modulation parts for AM
B	amplitude modulation parts for FM

Greek symbols

ϕ	initial phases of amplitude modulation
φ	initial phases of frequency modulation
θ	initial phases of frequency modulation
ω	angular speed

characteristic frequencies of local and distributed gear faults according to the unique behaviors of a planetary gearbox. There are still other works on planetary gear box fault diagnosis, such as [7,8] and etc. All these studies have made important contributions on fault diagnosis of planetary gearboxes.

However, it should be noticed that a planetary gearbox often runs under non-stationary operational conditions and the measured vibrations are rather complicated [1]. To use the measured vibration signals for planetary gear fault diagnostics, the degree of complexity and the non-stationary nature of the measured vibrations become two main obstacles for the effectiveness of condition monitoring. Researchers have made efforts to develop techniques to dealing with these two issues. Methods for dealing with non-stationary nature of vibrations of rotating machinery are developed, such as Non-Harmonic Fourier Analysis [9–12], Adaptive Multiscale Morphological Filter [13], New Cepstral Method [14–16], Time-Frequency Analysis [17,18] and Order Tracking Analysis [19]. However, compared with reported techniques under stationary conditions or constant speed and loads conditions, more studies for non-stationary operational conditions are still needed, specifically on planetary gearbox. While, with regard to the complexity of the measured vibration data, few works have been reported to cope with this issue. Nevertheless, it is of great importance for a proper diagnostic decision of a planetary gear system.

Thus, in this paper, phase angle based signal (PAS) from planetary gearbox vibrations under non-stationary operational conditions is studied. The main purpose of using phase information is to reduce the complexity of signal and ensure diagnostic capabilities of a planetary gearbox system under non-stationary operational conditions. Together with time-domain statistic indicator (sample entropy), phase angle based signal is investigated to realize enhanced diagnostics to a planetary gearbox under non-stationary operational conditions. In this way, a phase angle based diagnostic scheme is recommended to planetary gearbox condition monitoring. In this paper, the cosine phase angle is originally proposed for fault detection of rotating machine and together with sample entropy analysis, planetary gearbox faults are clearly detected and classified. The proposed scheme achieves the following advantages: (1) The complex amplitude modulation nature in the measured vibrations is largely excluded. This tremendously reduces the degree of complexity of the data. The influences from operational loads therefore are greatly deemphasized. (2) Though the amplitude information is deemphasized, the proposed angle based signal still contains characteristic fault information and is ready to be used for condition monitoring of planetary gear system. (3) Even under different operational conditions, the use of the proposed angle based signal can identify faults which is intractable by using the original measured vibrations.

In the following, Section 2 will first introduce phase angle in terms of a planetary gearbox system. Section 3 will interpret the phase angle data numerically. Section 4 is an experimental study to further demonstrate capabilities of the proposed scheme under the speed up condition of a real planetary gearbox system. Conclusion is made in Section 5.

2. Phase angle of planetary gear system

2.1. Discussions on the damage induced vibrations to fixed-axis and planetary gearboxes

In order to get a thorough understanding of phase angles, damage induced vibration models to planetary gearbox as well as a fixed-gear damaged induced vibration model are presented in [6] are summarized in the following for discussions:

1. Planetary gearbox – ring gear local damage

$$x(t) = \underbrace{[1 + A\cos(2\pi f_r t + \phi)]}_{\text{AM by relative rotation of ring}} \cos\left[2\pi f_m t + \underbrace{B\sin(2\pi f_r t + \varphi)}_{\text{FM by relative rotation of ring}} + \theta\right] \tag{1}$$