Measurement 48 (2014) 292–305

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Review

Condition monitoring and fault diagnosis of planetary gearboxes: A review

Yaguo Lei [a,*], Jing Lin [a], Ming J. Zuo [b,c], Zhengjia He [a]

[a] State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China
[b] School of Mechatronic Engineering, University of Electronic Science and Technology of China, Chengdu 611731, PR China
[c] Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta T6G2G8, Canada

ARTICLE INFO

Article history:
Received 4 March 2013
Received in revised form 28 October 2013
Accepted 7 November 2013
Available online 21 November 2013

Keywords:
Planetary gearboxes
Fault diagnosis
Modeling
Signal processing

ABSTRACT

Planetary gearboxes significantly differ from fixed-axis gearboxes and exhibit unique behaviors, which invalidate fault diagnosis methods working well for fixed-axis gearboxes. Much work has been done for condition monitoring and fault diagnosis of fixed-axis gearboxes, while studies on planetary gearboxes are not that many. However, we still notice that a number of publications on condition monitoring and fault diagnosis of planetary gearboxes have appeared in academic journals, conference proceedings and technical reports. This paper aims to review and summarize these publications and provide comprehensive references for researchers interested in this topic. The structures of a planetary gearbox as well as a fixed-axis one are briefly introduced and contrasted. The unique behaviors and fault characteristics of planetary gearboxes are identified and analyzed. Investigations on condition monitoring and fault diagnosis of planetary gearboxes are summarized based on the adopted methodologies. Finally, open problems are discussed and potential research topics are pointed out.

Contents

* Corresponding author. Tel.: +86 2983395041.
E-mail address: yaguolei@mail.xjtu.edu.cn (Y. Lei).

0263-2241/$ - see front matter
http://dx.doi.org/10.1016/j.measurement.2013.11.012

1. Introduction

Thanks to the advantages of large transmission ratio and strong load-bearing capacity, planetary (also called epicyclic) gearboxes are widely used in aerospace, automotive and heavy industry applications such as helicopters, wind turbines, and heavy trucks [1,2]. Planetary gearboxes generally operate under tough working environment. Their key components, for example, gears and bearings, are subject to damage modes such as fatigue crack and pitting [3]. A failure of planetary gearboxes may cause shutdown of the entire train and result in major economic losses and even human casualties. Condition monitoring and fault diagnosis of planetary gearboxes aims to prevent accidents and generate cost savings for users of planetary gearboxes.

Condition monitoring and fault diagnosis of gearboxes has been attracting considerably increasing attention [4–6]. Most investigations, however, focus on fixed-axis gearboxes in which all gears are designed to rotate around their own fixed centers [7–10] (see Fig. 1). Fundamentally different from fixed-axis gearboxes, planetary gearboxes refer to those including the transmission structure of planetary gear sets. An elementary planetary gear set, shown in Fig. 2a, is a compound gear system. The gear system contains a ring gear, a sun gear that rotates around its own center, and several planet gears that not only rotate around their own centers but also revolve around the center of the sun gear. With such a complex gear transmission structure, planetary gearboxes exhibit some unique behaviors, which

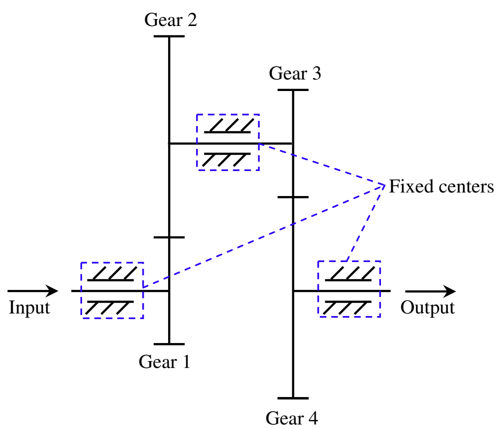

Fig. 1. Transmission diagram of a fixed-axis gear system having two meshing pairs.

invalidate fault diagnosis methods working well for fixed-axis gearboxes.

Compared with fixed-axis gearboxes, studies on condition monitoring and fault diagnosis of planetary gearboxes are not that many. However, they have grown at a rapid rate in recent years. Many publications on these studies appear every year in academic journals, conference proceedings and technical reports. In 2005, Samuel and Pines [11] thoroughly reviewed vibration-based diagnostic techniques for helicopter transmissions which contain a planetary gearbox, while a review specifically focusing on fault diagnosis of planetary gearboxes has not been reported yet based on the authors' literature search.

This paper aims to summarize and survey the research and development of condition monitoring and fault diagnosis of planetary gearboxes. It attempts to synthesize the individual pieces of information on this topic in context, therefore providing a comprehensive reference for researchers and helping them develop advanced research topics in this area. The survey is presented in terms of different methodologies used in fault diagnosis of planetary gearboxes, namely, modeling, signal processing and intelligent diagnosis.

The rest of the paper is organized as follows. Section 2 briefly compares the transmission structures of planetary gearboxes and fixed-axis ones, and identifies the unique behaviors and fault characteristics of planetary gearboxes. Section 3 reviews the publications on fault diagnosis of planetary gearboxes according to the used methodologies. Section 4 provides a summary by synthesizing the publications in a table and points out existing essential problems in reported research work. Section 5 describes prospects and identifies future research directions in this area. Concluding remarks are drawn in Section 6.

2. Brief introduction to planetary gearboxes

2.1. Transmission structures and operation behaviors

In this subsection, the transmission diagram of a fixed-axis gearbox containing two meshing pairs is given in Fig. 1 first before introducing that of a planetary gearbox. It is observed from Fig. 1 that all gears of the two meshing pairs rotate only around their own fixed centers. Gearboxes including only this kind of gear transmission structures are defined as fixed-axis ones accordingly.

In contrast, a planetary gear set have several planet gears which rotate around unfixed centers. As shown in

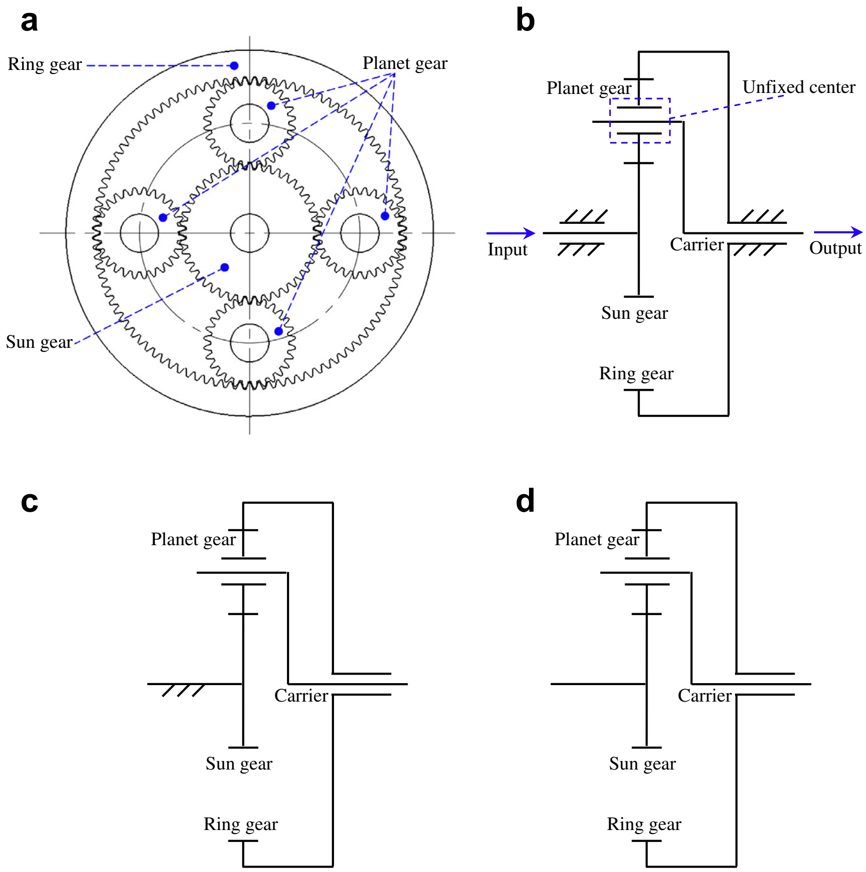

Fig. 2. (a) An elementary planetary gear set having 4 planet gears, (b) scheme of planetary gear set with the standstill ring gear, (c) scheme of planetary gear set with the standstill sun gear and (d) scheme of planetary gearbox set with the rotating sun gear and the rotating ring gear.

Fig. 2a, an example elementary planetary gear set has a ring gear, a sun gear that rotates around its own center, and four planet gears that not only rotate around their own unfixed centers but also revolve around the center of the sun gear. The planet gears are between the sun gear and the ring gear, and therefore mesh simultaneously with both of them. Generally, there are three elementary types of planetary gearboxes commonly used in modern industry. The three kinds of planetary gearboxes are given in Fig. 2b–d, respectively. Fig. 2b–d shows a planetary gearbox with the standstill ring gear, the standstill sun gear, and no standstill gear, respectively.

Because of their transmission structure, planetary gearboxes generally have the following behaviors, which are not observed in fixed-axis gearboxes.

(1) Multiple planet gears meshing simultaneously with the sun gear and the ring gear, and a large number of synchronous components (gears or bearings) in close proximity will excite similar vibrations in planetary gearboxes. These vibrations with different meshing phases couple with each other; as a result, some of the vibrations could be neutralized or cancelled [12].
(2) There are multiple and time-varying vibration transmission paths from gear meshing points to transducers, which are typically fixed on the housing of planetary gearboxes. These transmission paths may deteriorate or attenuate the vibration signal of faulty components through dissipation and interference effects [13]. In addition, torques or loads applied to the gearboxes may also add to the effects of nonlinear transmission paths [12]. All these effects would weaken the fault characteristics hidden in complicated vibration signals.
(3) Planetary gearboxes have different distributions in frequency spectra of vibration signals in comparison with fixed-axis gearboxes. For a pair of damaged meshing gears in fixed-axis gearboxes, fault characteristic frequencies, i.e. sidebands, emerge and symmetrically locate around the meshing frequency and its harmonics in the frequency spectra [14]. For both healthy and damaged planetary gearboxes, sidebands always appear in frequency spectra. In addition, the sidebands are generally asymmetric about the gear meshing frequency and its harmonics. It can be explained by the fact that multiple planet gears produce similar vibrations but with different

meshing phases, which causes some of the excitations of multiple gear meshes to be neutralized [15–17].

(4) Some components in planetary gearboxes generally operate under low rotating speeds because of the large transmission ratio. It is true that low-frequency characteristics are easily masked by heavy noise. Thus, it is significantly more difficult to discover the fault characteristics of low-speed components in planetary gearboxes.

Based on the behaviors described above, vibration signals measured from planetary gearboxes are more complex than those from fixed-axis gearboxes. Accordingly, the degree of difficulty of fault detection of planetary gearboxes increases, and the effectiveness of the detection methods developed for fixed-axis gearboxes is reduced or diminished when applied to planetary gearboxes.

2.2. Evaluation of characteristic frequencies

The characteristic frequencies, including the gear rotating frequency, the meshing frequency, etc., are critical to fault detection of gears. The identification of faults is related to the occurrence of the characteristic frequencies which is linked to the given fault. Hence, the characteristic frequencies of planetary gearboxes as well as fixed-axis gearboxes are provided in this subsection. The derivation of these characteristic frequencies is based on the gear transmission structures of the fixed-axis gearbox in Fig. 1 and the planetary gearbox with the standstill ring gear in Fig. 2b, respectively.

2.2.1. Fixed-axis gearboxes

Define the following notation:

N_j – is the number of teeth of gear j (j = 1,2,3,4).
f_j – is the rotating frequency of gear j (j = 1,2,3,4). The rotating frequency of gear 1.
(f_1) – is the input frequency of the whole gear transmission and is generally known beforehand.
i_k – is the transmission ratio of meshing pair k (k = 1,2), which is defined as the ratio between the rotating frequency of the driving gear and that of the driven gear in a meshing pair. Actually, it also equals the ratio between the number of teeth of the driven gear and that of the driving gear, for example, $i_1 = \frac{N_2}{N_1}$ and $i_2 = \frac{N_4}{N_3}$ in Fig. 1.
f_{m_k} – is the meshing frequency of meshing pair k (k = 1,2).

Then the characteristic frequencies, i.e. the rotating frequencies of each gear and the meshing frequencies of each meshing pair, can be expressed as a function of the input frequency (f_1) and the number of teeth of gears as follows. The equations of the characteristic frequencies are also summarized in Table 1.

$$f_2 = \frac{f_1}{i_1} = \frac{N_1}{N_2} f_1, \tag{1}$$

$$f_3 = f_2 = \frac{N_1}{N_2} f_1, \tag{2}$$

Table 1
Characteristic frequencies of the fixed-axis gearbox.

f_1	f_2	f_3	f_4	f_{m_1}	f_{m_2}
Known	$\frac{N_1}{N_2} f_1$	$\frac{N_1}{N_2} f_1$	$\frac{N_1 N_3}{N_2 N_4} f_1$	$N_1 f_1$	$\frac{N_1 N_3}{N_2} f_1$

$$f_4 = \frac{f_3}{i_2} = \frac{N_1 N_3}{N_2 N_4} f_1, \tag{3}$$

$$f_{m_1} = N_1 f_1, \tag{4}$$

and

$$f_{m_2} = N_3 f_3 = \frac{N_1 N_3}{N_2} f_1. \tag{5}$$

2.2.2. Planetary gearboxes

Based on the principles used in evaluating the characteristic frequencies of fixed-axis gearboxes, we can obtain the characteristic frequencies of the planetary gearbox in Fig. 2b. Make the following definitions first.

N_S, N_P and N_R – the number of teeth of the sun gear, a planet gear, and the ring gear, respectively.
M_P – the number of planet gears.
f_S, f_P, f_R and f_C – the rotating frequency of the sun gear, a planet gear, the ring gear and the carrier, respectively.
i – the transmission ratio of the planetary gearbox, which is defined as the ratio between the rotating frequency of the input shaft (the sun gear) and that of the output shaft (the carrier).
f_{p-p} – the pass frequency of the planet gears.
f_{m-p} – the meshing frequency of the planetary gearbox.

Since the transmission ratio is the key to evaluation of the characteristic frequencies of planetary gearboxes, its calculation process will be illustrated as follows [18], which is relatively complicated compared to that of fixed-axis gearboxes.

The ring gear of the planetary gear transmission shown in Fig. 2b is standstill. So, we have the following equation.

$$f_R = 0. \tag{6}$$

Transforming the planetary gear transmission into a fixed-axis transmission and utilizing the calculation principles of the fixed-axis one, the following equations are generated accordingly.

$$\begin{cases} \frac{f_S - f_C}{f_P - f_C} = -\frac{N_P}{N_S} \\ \frac{f_P - f_C}{f_R - f_C} = \frac{N_R}{N_P} \end{cases}. \tag{7}$$

Table 2
Characteristic frequencies of the planetary gearbox.

f_S	f_P	f_R	f_C	f_{p-p}	f_{m-p}
Known	$\frac{(N_P - N_R)N_S}{(N_R + N_S)N_P} f_S$	0	$\frac{N_S}{N_R + N_S} f_S$	$\frac{N_S M_P}{N_R + N_S} f_S$	$\frac{N_R N_S}{N_R + N_S} f_S$

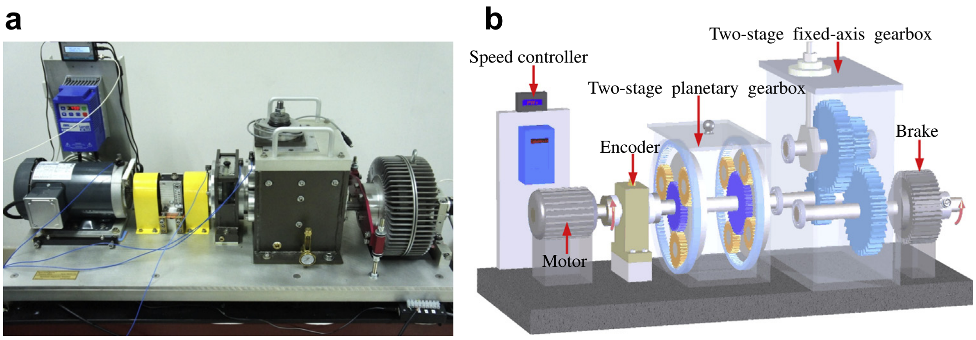

Fig. 3. (a) A planetary gearbox test rig and (b) its schematic model.

Substituting Eq. (6) into Eq. (7), we obtain the transmission ratio

$$i = \frac{f_S}{f_C} = 1 + \frac{N_R}{N_S}. \tag{8}$$

Based on the calculated transmission ratio, the characteristic frequencies can be written as a function of the rotating frequency of the sun gear (f_S) and the numbers of gear teeth by the following equations, which are summarized in Table 2 as well.

$$f_P = \frac{(N_P - N_R)N_S}{(N_R + N_S)N_P} f_S, \tag{9}$$

$$f_C = \frac{f_S}{i} = \frac{N_S}{N_R + N_S} f_S, \tag{10}$$

$$f_{p-p} = M_P f_C = \frac{N_S M_P}{N_R + N_S} f_S, \tag{11}$$

and

$$f_{m-p} = (f_S - f_C) N_S = \frac{N_R N_S}{N_R + N_S} f_S. \tag{12}$$

For the other two types of planetary gearboxes in Fig. 2c and d, the characteristic frequencies can be calculated in the same way. Refs. [19,20] provided the fundamentals by developing the characteristic frequencies of all three kinds of planetary gearboxes, which have influence on understanding the problems connected with condition monitoring and diagnosis of planetary gearboxes.

2.3. Illustrations using a planetary gearbox test rig

After introducing the behaviors and evaluating the characteristic frequencies of planetary gearboxes, we next use the vibration signals acquired from a test rig to illustrate the challenging issues in fault diagnosis of planetary gearboxes [21]. Fig. 3 displays the test rig and its schematic model. The test rig includes two gearboxes, a 3-hp motor for driving the gearboxes, and a magnetic brake for loading. The motor rotating speed is controlled by a speed controller. The load is provided by the magnetic brake and can be adjusted by a brake controller. As shown in Fig. 3b, there are two gearboxes in the test rig: a two-stage planetary gearbox and a two-stage fixed-axis gearbox. The two-stage planetary gearbox is the focus of our illustrations. In each stage of the planetary gearbox, an inner sun gear is surrounded by three or four rotating planet gears and a standstill outer ring gear. Torque is transmitted through the sun gear to the planet gears, which ride on a planetary carrier. The planetary carrier, in turn, transmits torque to the output shaft.

A vibration signal measured by an accelerometer with a sampling frequency of 5120 Hz under the healthy condition of the test rig is illustrated in Fig. 4a. Fig. 4b shows the frequency spectrum of the healthy vibration signal. To make a comparison with the healthy condition, another vibration signal with a cracked sun gear in the first stage is presented in Fig. 5a and b is its frequency spectrum. The two vibration signals are collected under the 40 Hz rotating frequency of the sun gear and the brake load of

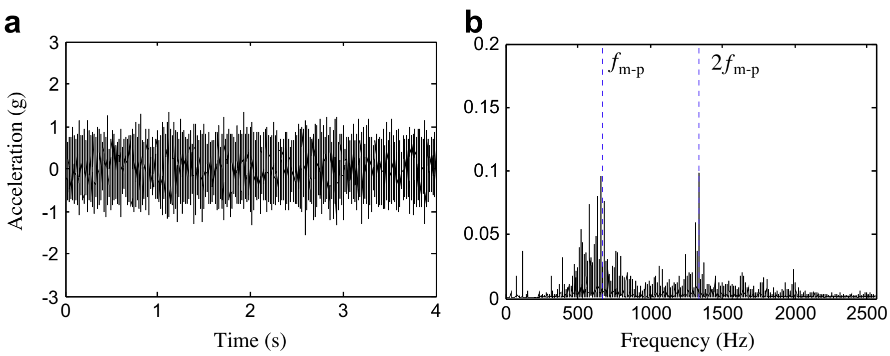

Fig. 4. Healthy condition: (a) a vibration signal and (b) the frequency spectrum.

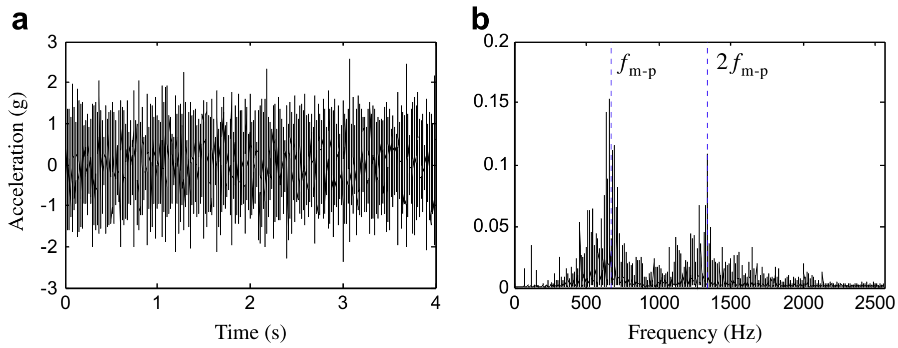

Fig. 5. Damaged condition: (a) a vibration signal and (b) the frequency spectrum.

13.5 Nm. Based on the frequency of the sun gear and the numbers of gear teeth, the meshing frequency of the first-stage planetary gearbox is calculated to be 666.67 Hz based on following Eq. (12). It is observed from both spectra in Figs. 4b and 5b that the amplitudes around the meshing frequency and its harmonics dominate the spectra. Furthermore, the sidebands around the meshing frequency and its harmonics are rather rich. This observation confirms the special behavior stated by item (3) in Subsection 2.1 that for both healthy and damaged planetary gearboxes, sidebands always appear and are asymmetric around the gear meshing frequency and its harmonics.

According to the above introduction, comparison and illustration, it is concluded that planetary gearboxes exhibit several unique behaviors, and as a result, condition monitoring and fault diagnosis of planetary gearboxes is of great challenge.

3. Review of condition monitoring and fault diagnosis of planetary gearboxes

To deal with the challenging issues in condition monitoring and fault diagnosis of planetary gearboxes, researchers have carried out numerous investigations and produced many publications in academic journals, conference proceedings and technical reports. Especially in recent years, publications on this research topic have increased at a rapid rate. A review on these publications will be presented in this section based on the adopted methodologies, i.e. modeling, signal processing and intelligent diagnosis.

3.1. Modeling methods

Various models of planetary gearboxes have been established and reported in the literature. Based on these models, the relations between the output response and the system parameters of the models were studied. The results from these studies may assist in understanding the behaviors of planetary gearboxes, thus representing a valuable aid in fault diagnosis of planetary gearboxes. This section is to summarize the publications on modeling of planetary gearboxes according to the studied issues, such as simulations of faults, simulations of vibration responses, and load sharing among the planet gears.

3.1.1. Simulations of faults

By the use of models, some fault modes, such as pitting, crack, and wear, were simulated on the components like gears or bearings in planetary gearboxes. This section is intended to describe these studies as follows. Chaari et al. [22] modeled tooth pitting and crack on the sun gear of planetary gearboxes and analyzed the influence of the faults on the gear mesh stiffness. In addition, they compared the dynamic responses of a healthy planetary gearbox and one with the presence of eccentricity and profile error through modeling [23]. Wang [24] compared the dynamics of models with and without tooth faults to improve the understanding of fault detection of planetary gearboxes. Park et al. [25] used a finite element based model to study the effects of the defect on the carrier of a planetary gear set in terms of stress distribution. Yuksel and Kahraman [26] constructed a computational model to study the influence of surface wear on the dynamic behaviors of a planetary gearbox. Hegadekatte et al. [27] implemented a finite element model to detect local wear in a micro planetary gear transmission. Patrick-Aldaco [28] established the physics based vibration models and proposed indicators for detecting faults occurring in planetary gearboxes. Cheng and Hu [29] put forward an approach based on physical models to detect damage in a planetary gearbox used in a helicopter transmission system. Moreover, they integrated the physical models, a three-step statistic algorithm and gray relational analysis for estimating damage levels of tooth pitting and crack on the sun gear [30–32].

In the above paragraph, we have reviewed the research work on modeling of fault simulation for planetary gearboxes. These models made a considerable contribution to condition monitoring and fault diagnosis of planetary gearboxes. The models, however, were developed based on many assumptions and simplifications. Therefore, their accuracy in simulating faults of planetary gearboxes is not high enough and needs to be further improved.

3.1.2. Simulations of vibration responses

As addressed in Section 2.1, the vibration responses of planetary gearboxes are more complex than those of fixed-axis gearboxes. Accordingly, to simulate the vibration responses and discover the vibration characteristics using models is an interesting research topic and has attracted a large amount of researchers. For example, Vicuña [33] proposed a phenomenological model to simulate the vibrations that may be measured by a hypothetical transducer mounted on the outer part of the ring gear. Jain and Hunt [34] presented an analytical model of a planetary gearbox to simulate the vibration response in the presence of faults on a planet bearing. Based on the model, the fault signatures of the planet bearing were determined. Feng and Zuo [35,36] investigated the spectral structure of vibration signals of planetary gearboxes, provided signal models of gear damage, and demonstrated the signal models using both experimental and industrial signals. Wu et al. [37] studied a planetary gearbox using multi-body dynamics models and observed that the dynamic responses of the model depend on the interaction of many components inside the gearbox. Mosher [38] explored the vibration spectra of planetary gearboxes using a kinematic model and compared the spectra with those of a helicopter planetary gear transmission. Mark and Hines [39] developed a mathematical model of a generic planetary gear system and derived the formulas for Fourier-series spectrum contributions of fixed-transducer responses.

The models focusing on the simulation of vibration responses of planetary gearboxes have been surveyed in the aforementioned paragraph. From the survey, it is observed that some interesting studies have been implemented and the vibration signals of different fault modes have been simulated by modeling. The simulated signals could improve the understanding of the vibration responses and enrich the database of fault diagnosis of planetary gearboxes, but the simulated signals are far from those of the real cases.

3.1.3. Load sharing among the planet gears

In a planetary gearbox, there are more than one planet gears, which are supposed to share the load uniformly. Actually, the planet gears generally undertake diverse loads due to manufacturing and assembly errors. Hence, research on load sharing among the planet gears is one of the most important issues in modeling of planetary gearboxes. With respect to this issue, researchers have carried out the following investigations. Ligata et al. [40] established a simplified model of a planetary gearbox to predict load sharing among the planet gears having manufacturing errors. Gu and Velex [41] constructed a lumped parameter model to simulate the effects of planet position errors on dynamic load sharing. Kahraman [42] developed a time-varying model to investigate the effect of manufacturing errors and assembly variations on the load sharing among the planet gears. Later, Bodas and Kahraman [43] extended this work and employed a contact mechanics model to further this study. Singh et al. [44] compared the theoretical study based on multi-body contact analysis models and the experimental results on load sharing in planetary gearboxes, and then they provided a physical explanation on the causes of the unequal load sharing phenomenon [45].

The previous paragraph summarizes the models constructed for investigating load sharing among the planet gears. Although this investigation is not very close to the research topic of condition monitoring and fault diagnosis of planetary gearboxes, the investigated results would potentially benefit this research topic.

3.1.4. Other issues

In addition, various models have been established to explore other issues in fault diagnosis of planetary gearboxes. This section will survey these models as follows. Inalpolat and Kahraman [46] proposed a simplified mathematical model to describe the mechanisms leading to modulation sidebands in planetary gearboxes. Subsequently, they [47] established a nonlinear time-varying dynamic model to predict modulation sidebands of planetary gearboxes and demonstrated the capability of the model. Bartelmus et al. [48] developed a model of a planetary gearbox to discover the correlation between varying loads and diagnostic features. Parker and Lin [49] advanced the modeling of planetary gearboxes and analytically examined critical factors affecting planetary gearbox noise and vibration. They further modeled the time-varying mesh stiffness of the sun-planet and ring-planet meshes and identified the operating conditions leading to parametric instability [50]. Guo and Parker [51] constructed lumped-parameter and finite element models of planetary gear systems involving bearing clearance, tooth separation, and mesh stiffness variation. Sun and Hu [52] established a lateral–torsional coupled model of a planetary gear system with multiple backlashes, time-varying mesh stiffness and error excitation. Utilizing an analytical model based on the interdependence between kinematics and kinetic relationship, Bahgat et al. [53] studied the effect of bearing clearances on the dynamics of planetary gearboxes.

3.2. Signal processing methods

Most publications on condition monitoring and fault diagnosis of planetary gearboxes are by the use of signal processing methods. This section aims to review these publications in terms of the following classifications: time-domain methods, frequency-domain methods, time–frequency-domain methods, and other signal processing methods.

3.2.1. Time-domain methods

Time-domain signal processing methods, such as statistical indicators and time synchronous averaging, are relatively easy and direct compared to both frequency-domain and time–frequency-domain methods. Therefore, they have been broadly adopted in condition monitoring and fault diagnosis of planetary gearboxes. For example, McFadden [15] presented a technique for calculating the time domain averages of the tooth meshing vibration of individual planet gears and of the sun gear. The technique was demonstrated with data collected from a planetary gearbox test rig with seeded damage [54]. Wu et al. [55,56] used indicators, such as root mean square and standard deviation, to distinguish between the cracked and healthy carrier of a helicopter planetary gearbox. Bartelmus and Zimroz [57] systematically investigated the influence of external varying load conditions on vibration signals of a planetary gearbox. They further introduced a diagnostic feature to monitor planetary gearboxes in time-varying operating conditions [58]. Smidt [59] attempted to mount transducers internally on the rotating carrier for vibration data collection and studied the synchronous averaging technique for condition monitoring of planetary gearboxes. Yip [60] used time synchronous averaging technique for preprocessing vibration data and then extracted health indicators from the preprocessed data to diagnose planetary gearboxes used in oil sands operations. Sparis and Vachtsevanos [61] selected two features based on time synchronous averaging signals to differentiate the faulty from the healthy carrier of a planetary gearbox. Keller and Grabill [62] modified several traditional diagnostic parameters, such as FM0 and FM4, targeting planetary gearbox applications. They found that only two parameters were relatively good for the lab test cell conditions and none of them were effective for the on-aircraft conditions. Lei et al. [21] presented two diagnostic parameters for detecting faults of planetary gearboxes.

The previous paragraph describes the literature of using time-domain methods to monitor and diagnose planetary gearboxes. The commonly used methods in time domain include time synchronous averaging and indicators. Because a planetary gearbox has a large number of synchronous components and a complex transmission structure, the traditional techniques and indicators suffer degradation and meet new problems.

3.2.2. Frequency-domain methods

Besides the time-domain methods mentioned above, frequency-domain methods have also been utilized by researchers for condition monitoring and fault diagnosis of planetary gearboxes. This section aims to describe the literature in which frequency-domain methods were employed. As an extension of the earlier analysis in Ref. [42], Mark [63] predicted the additional sidebands in frequency spectra produced by planet-carrier torque modulations, which might potentially mask the sidebands caused by damage in planetary gearboxes. To implement early fault detection of a planetary ring gear, Mark et al. [64] also suggested a simple frequency-domain method, which is able to eliminate the effects of transducers and structural-path-caused amplitude changes. Singleton [65] diagnosed the ring gear damage by examining the fault characteristic frequencies of each component in the planetary gearbox used in underground coal mining. Sparis and Vachtsevanos [66] designed the index vectors using fast Fourier transform to distinguish the faulty from the healthy carrier of helicopter planetary gearboxes. Hines et al. [13] developed a frequency domain feature called energy ratio based on the preprocessed signals by time synchronous average techniques to diagnose planetary carrier crack. McNames [1] applied Fourier series analysis to process the vibration data recorded from a helicopter planetary gearbox and tried to explain the source of the asymmetry phenomena observed in the spectra.

Since Fourier transform is the simplest frequency-domain method as well as a very fundamental tool to diagnose rotating components, it has been broadly used in condition monitoring and fault diagnosis of planetary gearboxes. However, in most papers, Fourier transform was combined with other preprocessing techniques to analyze the signals instead of used individually. This combination is due to the significant complexity and obvious nonstationarity of the signals generated by real planetary gearboxes.

3.2.3. Time–frequency-domain methods

Time–frequency-domain methods are generally much more effective than both time-domain and frequency-domain methods. Researchers have developed various time–frequency-domain methods, such as Wigner–Ville distribution, and wavelets, to diagnose planetary gearboxes. Chaari et al. [3] simulated two frequently encountered fault modes in planetary gearboxes, i.e. tooth pitting and crack, and then used the Wigner–Ville distribution to analyze the simulated signals. Zimroz et al. [67,68] constructed a procedure for estimating the instantaneous speed and analyzing vibrations of planetary gearboxes under non-stationary operating conditions. Meltzer and Ivanov [69,70] conducted fault diagnosis of a planetary gearbox in automobiles by means of a time–frequency analysis method. Schön [71] proposed an adaptive filtering technique in conjunction with time–frequency methods for indicating the health condition of a planetary gearbox. Liu et al. [72] utilized local mean decomposition to diagnose a seeded crack fault in a wind turbine. Based on ensemble empirical mode decomposition and energy separation algorithm, Feng et al. [73] proposed a joint amplitude and frequency demodulation method for diagnosing the sun gear damage of a planetary gearbox test rig. Saxena et al. [74] employed complex Morlet wavelets to extract features for distinguishing between the faulted and the healthy carrier of a helicopter planetary gearbox. Yu [75] presented the autocovariance of maximal energy wavelet coefficients to evaluate fault advancement of a planetary gearbox employed in oil sands operations. He et al. [76] used wavelet transform to process acoustic emission signals for localizing the gear fault in a planetary gearbox. Jiang et al. [77] introduced a denoising method based on adaptive Morlet wavelets and singular value decomposition and applied it to extract impulse features of a wind turbine planetary gearbox. Samuel and Pines [78] separated the vibration signal associated with planet gears by the use of multiple sensor methodology, and further analyzed the separated signal with continuous wavelet transform to detect the planet gear faults. They also performed the harmonic wavelet transform on vibration signals and obtained the mean square wavelet map to classify gear faults [79]. Moreover, they constructed wavelets by utilizing constrained adaptive lifting scheme for processing vibration signals of planetary gear transmissions [80–82].

The survey of the publications, which utilized time–frequency-domain methods in fault diagnosis of planetary gearboxes, has been presented in the above paragraph. By reviewing these publications, we find that most of them adopted wavelet transform in diagnosing planetary gearboxes. Actually, many novel or improved time–frequency methods have been introduced in recent years and with them, condition monitoring and fault diagnosis of planetary gearboxes is expected to be improved.

3.2.4. Other signal processing methods

There are still other signal processing methods used in condition monitoring and fault diagnosis of planetary gearboxes. They do not belong to time-domain, frequency-domain, or time–frequency-domain methods. We summarize these signal processing methods as follows. Zhang et al. [83–86] introduced a blind deconvolution de-noising scheme and demonstrated the scheme with a seeded crack on the carrier of a planetary gearbox. Barszcz and Randall [87] demonstrated the potential possibility of using spectral kurtosis for detecting a tooth crack on the ring in the planetary gearbox of a wind turbine. Bonnardot et al. [88] adopted an unsupervised order tracking algorithm to perform noise cancellation in the angular domain and to diagnose bearing faults in a helicopter planetary gearbox. Orchard and Vachtsevanos [89] developed an on-line particle filtering approach for failure prognosis of the carrier of helicopter planetary gear transmissions. Bartelmus [90] synthesized the work of his research group on vibration diagnostic methods and particularly stressed the application of cyclo-stationary analysis to fault signature extraction of planetary gearboxes. Zimroz and Bartelmus [91] investigated the use of cyclo-stationary properties of signals and then developed a spectral coherence map based diagnostic feature for monitoring a planetary gearbox used in the mining industry. Zimroz and Bartkowiak [92] studied the spectral structure of planetary gearbox vibration signals by principal component analysis. They also proposed canonical discriminant analysis to process 15-dimensional energy measurement based vectors of planetary gearboxes for visualizing them in a lower dimensional space [93]. Tumer and Huff [94] performed principal component analysis on the tri-axial data for monitoring helicopter gearboxes including a planetary stage. Lei et al. [95] put forward a noise-utilized method named adaptive stochastic resonance to diagnose the sun gear faults including a chipped tooth and a missing tooth. Villa et al. [96] presented an angular resampling method to diagnose unbalance and misalignment in a wind turbine drive train containing a planetary gear transmission. Randall [97] used signal separation techniques of bearings and gears and realized fault detection of planet bearings in helicopter gearboxes. Mosher [98] introduced an algorithm for separating the vibration signals of a planetary gear system into the signals attributable to each planet gear and based on the separated signals, the gear condition could be assessed. Blunt and Keller [12] proposed two methods, i.e. planet carrier method and planet separation method, to detect a fatigue crack on the carrier of a helicopter planetary gear transmission.

It is inspiring to see that other advanced signal processing techniques have been employed in the monitoring and diagnosis of planetary gearboxes. These advanced techniques include deconvolution, spectral kurtosis, cyclo-stationary analysis, stochastic resonance, etc. In fault diagnosis of planetary gearboxes, they have revealed their advantages like high accuracy as well as their shortcomings like weak robustness.

3.3. Intelligent diagnosis methods

Although signal processing methods have demonstrated some success in monitoring and diagnosing planetary gearboxes, the revelation of faults from the resulting signals requires a high degree of expertise. Intelligent fault diagnosis methods have the potential to overcome this shortcoming. Thus, various intelligent methods have been introduced and reported in fault diagnosis of planetary gearboxes. For example, Khazaee et al. [99] proposed a support vector machines based intelligent method to classify three health conditions of planetary gearboxes, namely, healthy, the ring gear with a worn tooth, and a planet gear with a worn tooth. Khawaja et al. [100] developed an approach based on least squares support vector machines to detect a growing crack on the carrier of a planetary gearbox. Liu et al. [101] combined support vector machines and linear discriminant analysis to identify several damage levels of planet gears inside a planetary gearbox test rig. They also proposed three methods for feature reduction and selection and applied them to fault level diagnosis [102–104]. Using the same data, Qu et al. [105] studied feature selection methods based on support vector machines for fault classification. Patrick et al. [106] designed an integrated framework of using Bayesian algorithms to detect faults and predict the remaining useful life of a helicopter planetary gearbox. Lei et al. [107,108] proposed a multi-sensor data fusion method with the use of adaptive neuro-fuzzy inference systems for identifying fault modes and damage levels of planetary gearboxes. Samuel and Pines [109] adopted the normalized energy metric as a feature vector and the self-organizing neural network as a classifier to automatically diagnose faults in a helicopter planetary gear transmission. Dong et al. [110] utilized hidden semi-Markov models to classify several health conditions of the planetary carrier in a helicopter transmission. Li et al. [111] extracted fault features from both vibration signals and acoustic emission signals, and then input the features into *K*-nearest neighbor algorithms to detect faults of planetary gearboxes. Dybała [112] presented a pattern recognition approach based on nearest boundary vector algorithms and applied it to fault detection of the planetary gearbox used in bucket wheel excavators. Zhao et al. [113] employed an ordinal ranking based approach to preserve the ordinal information and to identify damage levels of a planetary gearbox test rig. Chin et al. [114] investigated a fault pattern classification system including a quantization matrix and a multi-valued influence matrix and using this system, various fault modes in a helicopter planetary gearbox were identified. Bartkowiak and Zimroz [115] explored outlier analysis and one-class classification methods for fault diagnosis of planetary gearboxes operating under non-stationary conditions.

Aforementioned summary gives the description of applications of artificial intelligence to fault diagnosis of planetary gearboxes. It can be seen that many investigations have been carried out in this research area. Obviously, there is a need to use artificial intelligence but not solve only trivial topics, for example pitting development in simple gearboxes under stationary conditions.

3.4. Other studies

Besides the methods based on modeling, signal processing and intelligent diagnosis, other methods were applied to fault diagnosis of planetary gearboxes as well. This section is intended to summarize these methods. Fair [116] applied a synchronous sampling data acquisition system to a helical planetary gearbox to improve the understanding of the sideband characteristics in the collected signals. Lundvall and Klarbring [117] proposed a non-smooth Newton method to predict gear wear in a planetary gear set of a heavy truck transmission. Cheon and Parker [118] combined a nominal kinematic analysis with a hybrid finite element method to characterize the effects of manufacturing errors on the bearing forces of a planetary gearbox. Hayashi et al. [119] provided a measurement method of dynamic load sharing in planetary gear sets. Lu and Chu [120] discussed the methodologies based on vibration, noise and acoustic emission signals used in fault diagnosis of wind turbines which involves a planetary gearbox. Bartelmus [121] summarized all papers published by his research group on fault detection of complex gearboxes including planetary gear stages as well as fixed-axis ones.

4. Discussions on the state of the art

In Section 3, we have summarized many studies on condition monitoring and fault diagnosis of planetary gearboxes. A summary including all the literature in this area, however, is impossible and omission of some publications is inevitable since the literature on this research topic is numerous and diverse. We also notice that some publications relevant to this topic are written in other languages. Non-English publications, however, are not considered in this review because of the limitation of the authors' language proficiency.

To provide a shortcut to refer to the reported studies for researchers who are interested in this research area, in this section, we compile all references reviewed in Section 3 into Table 3 in terms of the diagnosis methodologies, i.e. modeling, signal processing and intelligent diagnosis. Based on the literature review in Section 3 and the references compiled in Table 3, the research community has recognized the significant differences in fault diagnosis between planetary gearboxes and fixed-axis ones. Accordingly, they have introduced new methods for condition monitoring and fault diagnosis of planetary gearboxes in recent years. Significant progress has been made on this topic. However, several essential problems still remain un-addressed in reported studies. They are pointed out as follows.

(1) The models reported in the published literature were established based on too many assumptions. Hence, they fail to reflect accurately the dynamic characteristics of real planetary gearboxes. In addition, most models were dedicated to the investigations of fault-free planetary gearboxes, while few focused on the studies of faulty ones. Actually, constructing and studying the models of faulty planetary gearboxes with various damage levels would be much more useful for fault detection of planetary gearboxes.
(2) The diagnosed objects in most of the literature are the sun gear, the ring gear or the carrier of planetary gearboxes. These components, similar to those in fixed-axis gearboxes, only rotate around their own fixed centers. Actually, planet gears perform the most complicated motion of rotating around their own centers, revolving around the center of the sun gear, and meshing simultaneously with both the sun gear and the ring gear. Thus, faults on the planet gears and their bearings are more difficult diagnose in planetary gearboxes. However, the references involving condition monitoring and fault diagnosis of planet gears and their bearings are very limited.

Table 3
Summary of the references on condition monitoring and fault diagnosis of planetary gearboxes.

Methodologies or issues	Refs.
Modeling	
• Simulations of faults	Chaari et al. [22,23], Wang [24], Park et al. [25], Yuksel and Kahraman [26], Hegadekatte et al. [27], Patrick-Aldaco [28], Cheng and Hu [29–32]
• Simulations of vibrations	Vicuña [33], Jain and Hunt [34], Feng and Zuo [35,36], Wu et al. [37], Mosher [38], Mark and Hines [39]
• Load sharing	Ligata et al. [40], Gu and Velex [41], Kahraman [42], Bodas and Kahraman [43], Singh et al. [44,45]
• Other issues	Inalpolat and Kahraman [46,47], Bartelmus et al. [48], Parker and Lin [49,50], Guo and Parker [51], Sun and Hu [52], Bahgat et al. [53]
Signal processing	
• Time domain	Hines et al. [13], McFadden [15,54], Lei et al. [21], Patrick-Aldaco [28], Bartelmus et al. [48], Cheng and Hu [29–32], Wu et al. [55–56], Bartelmus and Zimroz [57,58], Smidt [59], Yip [60], Sparis and Vachtsevanos [61], Keller and Grabill [62]
• Frequency domain	McNames [1], Hines et al. [13], Feng and Zuo [35,36], Mark et al. [63,64], Singleton [65], Sparis and Vachtsevanos [66]
• Time–frequency domain	Chaari et al. [3], Zimroz et al. [67,68], Meltzer and Ivanov [69,70], Schön [71], Liu et al. [72], Feng et al. [73], Saxena et al. [74], Yu [75], He et al. [76], Jiang et al. [77], Samuel and Pines [78–82]
• Other signal processing methods	Blunt and Keller [12], Zhang et al. [83–86], Barszcz and Randall [87], Bonnardot et al. [88], Orchard and Vachtsevanos [89], Bartelmus [90], Zimroz and Bartelmus [91], Zimroz and Bartkowiak [92,93], Tumer and Huff [94], Lei et al. [95], Villa et al. [96], Randall [97], Mosher [98]
Intelligent diagnosis	Cheng et al. [30–32], Khazaee et al. [99], Khawaja et al. [100], Liu et al. [101–104], Qu et al. [105], Patrick et al. [106], Lei et al. [107,108], Samuel and Pines [109], Dong et al. [110], Li et al. [111], Dybała [112], Zhao et al. [113], Chin et al. [114], Bartkowiak and Zimroz [115]
Other studies	Fair [116], Lundvall and Klarbring [117], Cheon and Parker [118], Hayashi et al. [119], Lu and Chu [120], Bartelmus [121]

(3) Many established condition monitoring and fault diagnosis methods for planetary gearboxes were geared to stationary operations. In addition, the elements in planetary gearboxes, like bearings, gears and shafts, were treated separately by researchers in these methods. As pointed out in Refs. [122,123], it is a wrong way of investigating on degradation process because this investigation did not have too much in common with real degradation process.
(4) Although researchers have introduced some methods for condition monitoring and fault diagnosis of planetary gearboxes, many of them are adapted from the methods suitable for fixed-axis gearboxes to planetary gearboxes. What is the underlying physics that justifies these adaptations? How to make these methods serve well for planetary gearboxes? Maybe, we cannot answer these questions and utilize these methods properly until we completely understand the special behaviors and the fault mechanism of planetary gearboxes.

5. Prospects

Aiming at the open research problems discussed in Section 4, the authors suggest the following prospects for consideration in future research of fault diagnosis of planetary gearboxes.

(1) Since the majority of the models constructed already simulate the healthy condition of planetary gearboxes, more models involving different fault modes and different damage levels, and considering varying working conditions need to be developed. By the use of these models, the relations between the response of the models and the key factors, such as system stiffness, model parameters, and fault severity degree, need to be explored. The revealed relations among these factors would provide substantial references and the needed knowledge for fault diagnosis of planetary gearboxes.
(2) As stressed in Section 2.1, in planetary gearboxes, multiple planet gears mesh simultaneously with the sun gear and the ring gear, and they excite similar vibrations but with different phases. These vibrations from the planet gears may couple with one another. The effect of this coupling may lead to the vibrations of faulty components to be neutralized or weakened. Thus, development of decoupling techniques to enhance and extract the fault mode signatures from multi-mode vibration signals is one of the most important issues in fault diagnosis of planetary gearboxes.
(3) To detect gearbox faults, transducers are commonly used to measure vibrations. They are typically fixed on the housing of gearboxes. Because planet gears revolve around the center of the sun gear in planetary gearboxes, there are time-varying vibration transmission paths from gear meshing points to the fixed transducers. Accordingly, additional modulation components besides those produced by faults will be introduced into the measured vibrations. How to separate and extract the modulation components of faults from those caused by time-varying transmission paths is a challenging problem.
(4) Many researchers demonstrated the effectiveness of their methods using their own typical data in detecting faults of planetary gearboxes, but there is no guarantee that these methods will still work well for other data. Actually, data measured from planetary gearboxes that are available in the open literature are few, unlike fixed-axis gearboxes, for which there are adequate open data collected either from experimental setups or from field operations. Therefore, conducting more experiments with different fault modes and severities, enriching the database and establishing the benchmarks are necessary to test the robustness of new diagnosis methods.
(5) It is a well-known fact that investigations of fault mechanisms and response characteristics of planetary gearboxes are of paramount importance. Hence, the authors suggest paying more attention to the following aspects: the relations between dynamic responses and health conditions, the evolution principle of faults, sensitive characteristics to faults, etc. With these additional investigations, we will be able to generate effective monitoring and diagnosis methods for planetary gearboxes.
(6) Considering the influence of fast varying load and rotation speed on vibration signals, there is a need to develop methods which can solve the problem of condition monitoring and fault diagnosis under varying operation, like planetary gearboxes in bucket wheel excavators. Moreover, considering that there is an interaction between the elements, the methods to be developed should also take into consideration that the machine is a unity of elements not a system of separated elements and not degradation of a specific element or fault [122,123].
(7) Moreover, vibration signals have been widely utilized in monitoring and diagnosing planetary gearboxes thanks to their ease of measurement and the rich information they contain. To improve the diagnosis accuracy of planetary gearboxes, multidimensional diagnosis techniques using a diverse group of information, like oil properties, wear debris, vibration, acoustic, load, speed, current, etc., are promising.

6. Concluding remarks

A review on condition monitoring and fault diagnosis of planetary gearboxes is presented in this paper. In the review, the complex structure of gear transmissions and the unique behaviors of planetary gearboxes are introduced and illustrated. Then, the reported literature on condition monitoring and fault diagnosis of planetary gearboxes is surveyed and summarized in terms of the used methodologies, such as modeling, signal processing, and intelligent diagnosis. Finally, open issues in this research area are outlined and possible topics for future research are discussed. We believe that this review has synthesized individual pieces of information on fault diagnosis of planetary gearboxes and provides a comprehensive reference for readers who are interested in this research area.

Acknowledgements

This research is supported by National Natural Science Foundation of China (51005172 and 51222503), New Century Excellent Talents in University (NCET-11-0421), Natural Sciences and Engineering Research Council of Canada (NSERC), Provincial Natural Science Foundation research project of Shaanxi (2013JQ7011) and Fundamental Research Funds for the Central Universities (2012jdgz01).

References

[1] J. McNames, Fourier series analysis of epicyclic gearbox vibration, Journal of Vibration and Acoustics 124 (2001) 150–152.
[2] Y.C. Guo, R.G. Parker, Analytical determination of mesh phase relations in general compound planetary gears, Mechanism and Machine Theory 46 (2011) 1869–1887.
[3] F. Chaari, T. Fakhfakh, M. Haddar, Dynamic analysis of a planetary gear failure caused by tooth pitting and cracking, Journal of Failure Analysis and Prevention 6 (2006) 73–78.
[4] Y.G. Lei, M.J. Zuo, Z.J. He, et al., A multidimensional hybrid intelligent method for gear fault diagnosis, Expert Systems with Applications 37 (2010) 1419–1430.
[5] M. Lebold, K. McClintic, R. Campbell, et al., Review of vibration analysis methods for gearbox diagnostics and prognostics, in: Proceedings of the 54th Meeting of the Society for Machinery Failure Prevention Technology, Virginia Beach, VA, May 1–4, 2000, pp. 623–634.
[6] R. Bajrić, D. Sprečić, N. Zuber, Review of vibration signal processing techniques towards gear pairs damage identification, International Journal of Engineering & Technology 11 (2011) 124–128.
[7] X.F. Fan, M.J. Zuo, Machine fault feature extraction based on intrinsic mode functions, Measurement Science and Technology 19 (2008) 1–12.
[8] X.F. Fan, M.J. Zuo, Gearbox fault detection using Hilbert and wavelet packet transform, Mechanical Systems and Signal Processing 20 (2006) 966–982.
[9] X.J. Zhou, Y.M. Shao, Y.G. Lei, et al., Time-varying meshing stiffness calculation and vibration analysis for a 16DOF dynamic model with linear crack growth in a pinion, the ASME, Journal of Vibration and Acoustics 134 (2012) 1–11.
[10] Y.G. Lei, M.J. Zuo, Gear crack level identification based on weighted *K* nearest neighbor classification algorithm, Mechanical Systems and Signal Processing 23 (2009) 1535–1547.
[11] P.D. Samuel, D.J. Pines, A review of vibration-based techniques for helicopter transmission diagnostics, Journal of Sound and Vibration 282 (2005) 475–508.
[12] D.M. Blunt, J.A. Keller, Detection of a fatigue crack in a UH-60A planet gear carrier using vibration analysis, Mechanical Systems and Signal Processing 20 (2006) 2095–2111.
[13] J.A. Hines, D.S. Muench, J.A. Keller, et al., Effects of time-synchronous averaging implementations on HUMS features for UH-60A planetary carrier cracking, American Helicopter Society 61st Annual Forum, Grapevine, TX, June 1–3, 2005.
[14] P.D. McFadden, Detecting fatigue cracks in gears by amplitude and phase demodulation of the meshing vibration, Journal of Vibration, Acoustics, Stress, and Reliability in Design 108 (1986) 165–170.
[15] P.D. McFadden, A technique for calculation the time domain averages of the vibration of the individual planet gears and the sun gear in an epicyclic gearbox, Journal of Sound and Vibration 144 (I) (1991) 163–172.
[16] P.D. McFadden, J.D. Smith, An explanation for the asymmetry of the modulation sidebands about the tooth meshing frequency in epicyclic gear vibration, Proceedings of the Institution of Mechanical Engineers 199 (1985) 65–70.
[17] P.D. McFadden, Examination of a technique for the early detection of failure in gears by signal processing of the time domain average of the meshing vibration, Mechanical Systems and Signal Processing 1 (1987) 173–183.
[18] X.F. Fan, M.J. Zuo, Condition monitoring of low speed planetary gearboxes, Technical Report, Department of Mechanical Engineering, University of Alberta, February 9, 2006, 32 pages.
[19] W. Bartelmus, R. Zimroz, Vibration spectra characteristics frequencies for condition monitoring of mine machinery compound and complex gearboxes, Scientific Papers of the Institute of Mining of the Wroclaw University of Technology, Mining and geology XVI 2011 Wroclaw, 17–34.
[20] W. Bartelmus, Fundamentals for condition monitoring and diagnostics for driving bucket wheel system with overload mechanism of bucket wheel excavator, Scientific Papers of the Institute of Mining of the Wroclaw University of Technology, Mining and. and geology XVI 2011 Wroclaw, 5–16.
[21] Y.G. Lei, D.T. Kong, J. Lin, et al., Fault detection of planetary gearboxes using new diagnostic parameters, Measurement Science and Technology 23 (2012). 0556051–10.
[22] F. Chaari, T. Fakhfakh, M. Haddar, Analytical investigation on the effect of gear teeth faults on the dynamic response of a planetary gear set, Noise & Vibration Worldwide 37 (2009) 9–15.
[23] F. Chaari, T. Fakhfakh, R. Hbaieb, et al., Influence of manufacturing errors on the dynamic behavior of planetary gears, The International Journal of Advanced Manufacturing Technology 27 (2006) 738–746.
[24] Z.W. Wang, Dynamic modelling of planetary gear systems for gear tooth fault detection, Master Thesis, Curtin University of Technology, Perth, Australia, 2010.
[25] S. Park, J. Lee, U. Moon, et al., Failure analysis of a planetary gear carrier of 1200HP transmission, Engineering Failure Analysis 17 (2010) 521–529.
[26] C. Yuksel, A. Kahraman, Dynamic tooth loads of planetary gear sets having tooth profile wear, Mechanism and Machine Theory 39 (2004) 695–715.
[27] V. Hegadekatte, J. Hilgert, O. Kraft, et al., Multi time scale simulations for wear prediction in micro-gears, Wear 268 (2010) 316–324.
[28] R. Patrick-Aldaco, A model based framework for fault diagnosis and prognosis of dynamical systems with an application to helicopter transmissions, Doctoral Thesis, Georgia Institute of Technology, Georgia, USA, 2007.
[29] Z. Cheng, N.Q. Hu, Quantitative damage detection for planetary gear sets based on physical models, Chinese Journal of Mechanical Engineering 24 (2011) 1–7.
[30] Z. Cheng, N.Q. Hu, F.S. Gu, et al., Pitting damage levels estimation for planetary gear sets based on model simulation and grey relational analysis, Transactions of the Canadian Society for Mechanical Engineering 35 (2011) 403–417.
[31] Z. Cheng, N.Q. Hu, X.F. Zhang, Crack level estimation approach for planetary gearbox based on simulation signal and GRA, Journal of Sound and Vibration 331 (2012) 5853–5863.
[32] Z. Cheng, N.Q. Hu, M.J. Zuo, et al., Crack level estimation approach for planetary gear sets based on simulation signal and GRA, Journal of Physics: Conference Series 364 (2012) 0120761–120769.
[33] C.M. Vicuña, Theoretical frequency analysis of vibrations from planetary gearboxes, Forsch Ingenieurwes 76 (2012) 15–31.
[34] S. Jain, H. Hunt, Vibration response of a wind-turbine planetary gear set in the presence of a localized planet bearing defect, in: ASME 2011 International Mechanical Engineering Congress and Exposition (IMECE2011), Denver, Colorado, USA, November 11–17, 2011, pp. 943–952.
[35] Z.P. Feng, M.J. Zuo, Vibration signal models for fault diagnosis of planetary gearboxes, Journal of Vibration and Acoustics 331 (2012) 4919–4939.
[36] Z.P. Feng, M.J. Zuo, Fault diagnosis of planetary gearboxes via torsional vibration signal analysis, Mechanical Systems and Signal Processing 36 (2013) 401–421.
[37] X. Wu, J. Meagher, A. Sommer, A differential planetary gear model with backlash and teeth damage, Shock and Vibration 5 (2011) 203–215.
[38] M. Mosher, Understanding vibration spectra of planetary gear systems for fault detection, in: ASME Design Engineering Technical Conferences, Chicago, Illinois, USA, September 2–6, 2003, pp. 1–8.
[39] W.D. Mark, J.A. Hines, Stationary transducer response to planetary-gear vibration excitation with non-uniform planet loading, Mechanical Systems and Signal Processing 23 (2009) 1366–1381.
[40] H. Ligata, A. Kahraman, A. Singh, A closed-form planet load sharing formulation for planetary gear sets using a translational analogy, Journal of Mechanical Design 131 (2009) 1–7.

[41] X. Gu, P. Velex, A dynamic model to study the influence of planet position errors in planetary gears, Journal of Sound and Vibration 331 (2012) 1–20.
[42] A. Kahraman, Load sharing characteristics of planetary transmissions, Mechanism and Machine Theory 29 (1994) 1151–1165.
[43] A. Bodas, A. Kahraman, Influence of carrier gear manufacturing errors on the static load sharing behavior of planetary gear sets, JSME International Journal 47 (2004) 908–915.
[44] A. Singh, A. Kahraman, H. Ligata, Internal gear strains and load sharing in planetary transmissions–model and experiments, in: Proceedings of the ASME 2007 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Las Vegas, Nevada, USA, September 4–7, 2007.
[45] A. Singh, Load sharing behavior in epicyclic gears: physical explanation and generalized formulation, Mechanism and Machine Theory 45 (2010) 511–530.
[46] M. Inalpolat, A. Kahraman, A theoretical and experimental investigation of modulation sidebands of planetary gear sets, Journal of Sound and Vibration 323 (2009) 677–696.
[47] M. Inalpolat, A. Kahraman, A dynamic model to predict modulation sidebands of a planetary gear set having manufacturing errors, Journal of Sound and Vibration 329 (2010) 371–393.
[48] W. Bartelmus, F. Chaari, R. Zimroz, et al., Modelling of gearbox dynamics under time-varying nonstationary load for distributed fault detection and diagnosis, European Journal of Mechanics A/Solids 29 (2010) 637–646.
[49] R.G. Parker, J. Lin, Modeling, modal properties, and mesh stiffness variation instabilities of planetary gears, Technical Report, NASA/CR-2001-210939, ARL-CR-462, Ohio State University Columbus, May 2001.
[50] J. Lin, Planetary gear parametric instability caused by mesh stiffness variation, Journal of Sound and Vibration 249 (1) (2002) 129–145.
[51] Y. Guo, R.G. Parker, Nonlinear phenomena in planetary gears using harmonic balance method, in: 7th European Nonlinear Dynamics Conference, Rome, Italy, July 24-29, 2011.
[52] T. Sun, H.Y. Hu, Nonlinear dynamics of a planetary gear system with multiple clearances, Mechanism and Machine Theory 38 (2003) 1371–1390.
[53] B.M. Bahgat, M.O.M. Osman, R.V. Dukkipati, On the dynamic gear tooth loading of planetary gearing as affected by bearing clearances in high-speed machinery, Journal of Mechanisms, Transmissions, and Automation in Design 107 (1985) 430–436.
[54] P.D. McFadden, I.M. Howard, The detection of seeded faults in an epicyclic gearbox by signal averaging of the vibration, Technical Report, Propulsion Report 183, Aeronautical Research Laboratory, Melbourne, Australia, October 1990.
[55] B.Q. Wu, A. Saxena, T.S. Khawaja, et al., An approach to fault diagnosis of helicopter planetary gears, in: Autotestcon 2004 Proceedings, Atlanta, GA, USA, September 20–23, 2004, pp. 475–481.
[56] B.Q. Wu, A. Saxena, R. Patrick, et al., Vibration monitoring for fault diagnosis of helicopter planetary gears, in: Proceedings of the 16th IFAC World Congress, Prague, 2005, pp. 126–131.
[57] W. Bartelmus, R. Zimroz, Vibration condition monitoring of planetary gearbox under varying external load, Mechanical Systems and Signal Processing 23 (2009) 246–257.
[58] W. Bartelmus, R. Zimroz, A new feature for monitoring the condition of gearboxes in non-stationary operating conditions, Mechanical Systems and Signal Processing 23 (2009) 1528–1534.
[59] M.R. Smidt, Internal vibration monitoring of a planetary gearbox, Master Thesis, University of Pretoria, Pretoria, South Africa, 2010.
[60] L. Yip, Analysis and modelling of planetary gearbox vibration data for early fault detection, Master Thesis, University of Toronto, Toronto, Canada, 2011.
[61] P. Sparis, G. Vachtsevanos, A helicopter planetary gear carrier plate crack analysis and feature extraction based on ground and aircraft tests, in: Intelligent Control, Proceedings of the 2005 IEEE International Symposium on, Mediterrean Conference on Control and Automation, Limassol, Cyprus, June 27–29, 2005, pp. 646–651.
[62] J.A. Keller, P. Grabill, Vibration monitoring of UH-60A main transmission planetary carrier fault, in: American Helicopter Society 59th Annual Forum, Phoenix, Arizona, USA, May 6–8, 2003.
[63] W.D. Mark, Stationary transducer response to planetary-gear vibration excitation II: effects of torque modulations, Mechanical Systems and Signal Processing 23 (2009) 2253–2259.
[64] W.D. Mark, H. Lee, R. Patrick, et al., A simple frequency-domain algorithm for early detection of damaged gear teeth, Mechanical Systems and Signal Processing 24 (2010) 2807–2823.
[65] K. Singleton, Analysis of two stage planetary gearbox vibration, Technical Report, KSC Consulting LLC, September, 2006, 12 pages.
[66] P. Sparis, G. Vachtsevanos, Automatic diagnostic feature generation via the Fast Fourier Transform, Technical Report, 13 pages <http://utopia.duth.gr/~sparis/Automatic%20Feature%20Generation.pdf>.
[67] R. Zimroz, F. Millioz, N. Martin, A procedure of vibration analysis from planetary gearbox under non-stationary cyclic operations for instantaneous frequency estimation in time-frequency domain, in: Conference on Condition Monitoring and Machinery Failure Prevention Technologies (CM and MFPT 2010), United Kingdom, May 1–3, 2011.
[68] R. Zimroz, J. Urbanek, T. Barszcz, et al., Measurement of instantaneous shaft speed by advanced vibration signal processing – application to wind turbine gearbox, Metrology and Measurement Systems XVIII (2011) 701–712.
[69] G. Meltzer, Y.Y. Ivanov, Fault detection in gear drives with non-stationary rotational speed – Part I: The time-frequency approach, Mechanical Systems and Signal Processing 17 (5) (2003) 1033–1047.
[70] G. Meltzer, Y.Y. Ivanov, Fault detection in gear drives with non-stationary rotational speed – Part II: The time-frequency approach, Mechanical Systems and Signal Processing 17 (2) (2003) 273–283.
[71] P.P. Schön, Unconditionally convergent time domain adaptive and time-frequency techniques for epicyclic gearbox vibration, Mechanical and Aeronautical Engineering, Master Thesis, University of Pretoria, Pretoria, South Africa, June, 2005.
[72] W.Y. Liu, W.H. Zhang, J.G. Han, et al., A new wind turbine fault diagnosis method based on the local mean decomposition, Renewable Energy 48 (2012) 411–415.
[73] Z.P. Feng, M. Liang, Y. Zhang, et al., Fault diagnosis for wind turbine planetary gearboxes via demodulation analysis based on ensemble empirical mode decomposition and energy separation, Renewable Energy 47 (2012) 112–126.
[74] A. Saxena, B.Q. Wu, G. Vachtsevanos, A methodology for analyzing vibration data from planetary gear systems using complex Morlet wavelets, in: 2005 American Control Conference, Portland, OR, USA, June 8–10, 2005, pp. 4730–4735.
[75] J. Yu, Early fault detection for gear shaft and planetary gear based on wavelet and hidden Markov modeling, Doctoral Thesis, University of Toronto, Toronto, Canada, 2011.
[76] D. He, P. Manon, R. Li, et al., Gear fault location detection for split torque gearbox using AE sensors, in: Annual Conference of the Prognostics and Health Management Society, Chicago, USA, 2010, pp. 1–18.
[77] Y.H. Jiang, B.P. Tang, Y. Qin, et al., Feature extraction method of wind turbine based on adaptive Morlet wavelet and SVD, Renewable Energy 36 (2011) 2146–2153.
[78] P.D. Samuel, D.J. Pines, Vibration separation methodology for planetary gear health monitoring, Smart Structures and Materials 3985 (2000) 250–260.
[79] P.D. Samuel, D.J. Pines, Health monitoring/damage detection of a rotorcraft planetary geartrain system using piezoelectric sensors, in: Proc. SPIE 3041, Smart Structures and Materials 1997: Smart Structures and Integrated Systems, San Diego, California, USA, March 03, 1997, pp. 44–53.
[80] P.D. Samuel, D.J. Pines, Constrained adaptive lifting and the CAL4 metric for helicopter transmission diagnostics, Journal of Sound and Vibration 319 (2009) 698–718.
[81] P.D. Samuel, D.J. Pines, Helicopter transmission diagnostics using constrained adaptive lifting, in: American Helicopter Society 59th Annual Forum. Phoenix, Arizona, USA, May 6–8, 2003, pp. 141–149.
[82] P.D. Samuel, J.K. Conroy, D.J. Pines, Planetary transmission diagnostics, Technical Report NASA/CR-2004-213068, University of Maryland, Maryland, May 2004, 90 pages.
[83] B. Zhang, T. Khawaja, R. Patrick, et al., A novel blind deconvolution de-noising scheme in failure prognosis, Transactions of the Institute of Measurement and Control 32 (2010) 3–30.
[84] B. Zhang, T. Khawaja, R. Patrick, et al., Application of blind deconvolution denoising in failure prognosis, IEEE Transactions on Instrumentation and Measurement 58 (2009) 303–310.
[85] B. Zhang, T. Khawaja, R. Patrick, et al., Blind deconvolution denoising for helicopter vibration signals, IEEE/ASME Transactions on Mechatronics 13 (2008) 558–565.
[86] B. Zhang, T. Khawaja, R. Patrick, et al., Use of blind deconvolution de-noising scheme in failure prognosis, in: Autotestcon 2007 IEEE, Baltimore, Maryland, USA, September 17–20, 2007, pp. 561–566.
[87] T. Barszcz, R.B. Randall, Application of spectral kurtosis for detection of a tooth crack in the planetary gear of a wind turbine, Mechanical Systems and Signal Processing 23 (2009) 1352–1365.

[88] F. Bonnardot, R.B. Randall, J. Antoni, Enhanced unsupervised noise cancellation using angular resampling for planetary bearing fault diagnosis, International Journal of Acoustics and Vibration 9 (2004) 51–60.

[89] M.E. Orchard, G.J. Vachtsevanos, A particle filtering approach for on-line failure prognosis in a planetary carrier plate, International Journal of Fuzzy Logic and Intelligent Systems 7 (2007) 221–227.

[90] W. Bartelmus, Vibration Diagnostic Method for Planetary Gearboxes Under Varying External Load With Regard to Cyclostationary Analysis, Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław, 2009.

[91] R. Zimroz, W. Bartelmus, Gearbox condition estimation using cyclo-stationary properties of vibration signal, Key Engineering Materials 413–414 (2009) 471–478.

[92] R. Zimroz, A. Bartkowiak, Investigation on spectral structure of gearbox vibration signals by principal component analysis for condition monitoring purposes, Journal of Physics: Conference Series 305 (2011). 0120751–11.

[93] R. Zimroz, A. Bartkowiak, Two simple multivariate procedures for monitoring planetary gearboxes in non-stationary operating conditions, Mechanical Systems and Signal Processing (2012). <http://dx.doi.org/10.1016/j.ymssp.2012.03.022>.

[94] I.Y. Tumer, E.M. Huff, Using triaxial accelerometer data for vibration monitoring of helicopter gearboxes, in: Proceedings of ASME Design Engineering Technical Conferences, Pittsburgh, Pennsylvania, USA, September 9–12, 2001, pp. 1–11.

[95] Y.G. Lei, D. Han, J. Lin, et al., Planetary gearbox fault diagnosis using an adaptive stochastic resonance method, Mechanical Systems and Signal Processing (2012). <http://dx.doi.org/10.1016/j.ymssp.2012.06.021>.

[96] L.F. Villa, A. Reñones, J.R. Perán, et al., Statistical fault diagnosis based on vibration analysis for gear test-bench under non-stationary conditions of speed and load, Mechanical Systems and Signal Processing 29 (2012) 436–446.

[97] R.B. Randall, Detection and diagnosis of incipient bearing failure in helicopter gearboxes, Engineering Failure Analysis 11 (2004) 177–190.

[98] M. Mosher, Results from a new separation algorithm for planetary gear system vibration measurements, in: Proceedings of ASME 2005 International Design Engineering Technical Conferences &Computers and Information in Engineering Conference, Long Beach, California, USA, September 24–28, 2005.

[99] M. Khazaee, H. Ahmadi, M. Omid, et al., An appropriate approach for condition monitoring of planetary gearbox based on fast Fourier transform and least-square support vector machine, International Journal of Multidisciplinary Sciences and Engineering 3 (2012) 22–26.

[100] T.S. Khawaja, G. Georgoulas, G. Vachtsevanos, An efficient novelty detector for online fault diagnosis based on least squares support vector machines, in: IEEE Autotestcon (2008), Salt Lake City, UT, USA, September 8–11, 2008.

[101] Z.L. Liu, J. Qu, M.J. Zuo, et al., Classification of gear damage levels in planetary gearboxes, in: 2011 IEEE International Conference on Computational Intelligence for Measurement Systems and Applications, Ottawa, Canada, September 19–21, 2011.

[102] Z.L. Liu, M.J. Zuo, H.B. Xu, Feature ranking for support vector machine classification and its application to machinery fault diagnosis, Proceedings of the Institution of Mechanical Engineers, Part C, Journal of Mechanical Engineering Science (2012). <http://dx.doi.org/10.1177/0954406212469757>.

[103] Z.L. Liu, M.J. Zuo, H.B. Xu, Fault diagnosis for planetary gearboxes using multi-criterion fusion feature selection framework, Journal of Mechanical Engineering and Science (2012). <http://dx.doi.org/10.1177/0954406212468407>.

[104] Z.L. Liu, J. Qu, Ming J. Zuo, et al., Fault level diagnosis for planetary gearboxes using hybrid kernel feature selection and kernel Fisher discriminant analysis, International Journal of Advanced Manufacturing Technology 67 (2013) 1217–1230.

[105] J. Qu, Z. Liu, M.J. Zuo, et al., Feature selection for damage degree classification of planetary gearboxes using support vector machine, Mechanical Engineering Science 225 (2011) 2250–2264.

[106] R. Patrick, M.E. Orchard, B. Zhang, et al., An integrated approach to helicopter planetary gear fault diagnosis and failure prognosis, in: Proceedings of 2007 IEEE Autotestcon, Baltimore, MD, USA, September 17–20, 2007, pp. 547–552.

[107] Y.G. Lei, J. Lin, Z.J. He, et al., A method based on multi-sensor data fusion for fault detection of planetary gearboxes, Sensors 12 (2012) 2005–2017.

[108] Y.G. Lei, J. Lin, Z.J. He, Fault level identification of planetary gearboxes based on information fusion, in: Proceedings of the 24th International Congress on Condition Monitoring and Diagnostics Engineering Management, Clarion Hotel Stavanger, Stavanger, Norway, May 30–June 1, 2011, pp. 185–188.

[109] P.D. Samuel, D.J. Pines, Classifying helicopter gearbox faults using a normalized energy metric, Smart Materials and Structures 10 (2001) 145–153.

[110] M. Dong, D. He, P. Banerjee, et al., Equipment health diagnosis and prognosis using hidden semi-Markov models, The International Journal of Advanced Manufacturing Technology 30 (2006) 738–749.

[111] R.Y. Li, D. He, E. Bechhoefer, Investigation on fault detection for split torque gearbox using acoustic emission and vibration signals, in: Annual Conference of the Prognostics and Health Management Society 2009, San Diego, CA, USA, September 27–October 1, 2009, pp. 1–11.

[112] J. Dybała, Vibrodiagnostics of gearboxes using NBV-based classifier: a pattern recognition approach, Mechanical Systems and Signal Processing (2012). <http://dx.doi.org/10.1016/j.ymssp.2012.08.021>.

[113] X.M. Zhao, M.J. Zuo, Z.L. Liu, et al., Diagnosis of artificially created surface damage levels of planet gear teeth using ordinal ranking, Measurement 46 (2012) 132–144.

[114] H. Chin, K. Danai, D.G. Lewicki, Fault detection of helicopter gearboxes using the muti-valued influence matrix method, Technical Report NASA 92-C-015, University of Massachusetts, June 1993.

[115] A. Bartkowiak, R. Zimroz, Outliers analysis and one class classification approach for planetary gearbox diagnosis, Journal of Physics: Conference Series 305 (2011). 0120311–11.

[116] C.E. Fair, Synchronous sampling sideband orders from helical planetary gear sets, Master Thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 1998.

[117] O. Lundvall, A. Klarbring, Simulation of wear by use of a nonsmooth Newton method: a spur gear application, Mechanics of Structures and Machines 29 (2001) 223–238.

[118] G. Cheon, R.G. Parker, Influence of manufacturing errors on the dynamic characteristics of planetary gear systems, KSME International Journal 18 (2004) 606–621.

[119] T. Hayashi, Y.X. Li, I. Hayashi, et al., Measurement and some discussions on dynamic load sharing in planetary gears, Bulletin of JSME 29 (1986) 2290–2298.

[120] W. X. Lu, F.L. Chu, Condition monitoring and fault diagnostics of wind turbines, in: 2010 Prognostics & System Health Management Conference, Macao, China, January 12–14, 2010, pp. 1–11.

[121] W. Bartelmus, Gearbox damage process, Journal of Physics: Conference Series 305 (2011). 0120291-10.

[122] W. Bartelmus, Object and operation factor oriented diagnostics, in: Proceedings of the Second International Conference on Condition Monitoring in Non-Stationary Operations, Springer, 2012, pp. 11–23.

[123] W. Bartelmus, Editorial statement, Mechanical Systems and Signal Processing 38 (2013) 1–4.