Mechanical Systems and Signal Processing 98 (2018) 16–31

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Instantaneous speed jitter detection via encoder signal and its application for the diagnosis of planetary gearbox

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ARTICLE INFO

Article history:
Received 19 March 2016
Received in revised form 22 December 2016
Accepted 24 April 2017
Available online 2 May 2017

Keywords:
Planetary gearbox
Local polynomial differentiator
Instantaneous angular speed
Health monitoring
Fault diagnosis

ABSTRACT

In modern rotating machinery, rotary encoders have been widely used for the purpose of positioning and dynamic control. The study in this paper indicates that, the encoder signal, after proper processing, can be also effectively used for the health monitoring of rotating machines. In this work, a Kurtosis-guided local polynomial differentiator (KLPD) is proposed to estimate the instantaneous angular speed (IAS) of rotating machines based on the encoder signal. Compared with the central difference method, the KLPD is more robust to noise and it is able to precisely capture the weak speed jitters introduced by mechanical defects. The fault diagnosis of planetary gearbox has proven to be a challenging issue in both industry and academia. Based on the proposed KLPD, a systematic method for the fault diagnosis of planetary gearbox is proposed. In this method, residual time synchronous time averaging (RTSA) is first employed to remove the operation-related IAS components that come from normal gear meshing and non-stationary load variations, KLPD is then utilized to detect and enhance the speed jitter from the IAS residual in a data-driven manner. The effectiveness of proposed method has been validated by both simulated data and experimental data. The results demonstrate that the proposed KLPD-RTSA could not only detect fault signatures but also identify defective components, thus providing a promising tool for the health monitoring of planetary gearbox.

1. Introduction

During the past decades, a variety of techniques have been developed for the condition based maintenance (CBM) of rotating machinery, including vibration analysis, acoustic emission (AE), temperature analysis and wear debris analysis. Among these techniques, vibration analysis is perhaps the most widely used tool for condition monitoring, fault diagnosis as well as prognosis [1,2]. Despite its superior performance, the vibration signal, however, is not always available in practical applications. To name a few, in the tool condition monitoring during the cutting process, the vibration sensor might be easily damaged by the cutting chips and coolant; in the health assessment of a robotic arm, it is usually difficult to mount an accelerometer due to the complicated motion trajectory of the arm; in some other applications, the installation of a vibration sensor is not allowed due to environment/space limitations or cost considerations. Therefore, how to monitor the machine

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http://dx.doi.org/10.1016/j.ymssp.2017.04.033
0888-3270/

health conditions in a sensor-less environment, where the vibration sensor is not available, has become a challenging problem.

With the advancement of measurement and control techniques, more and more rotary encoders are equipped in rotating machinery such as high speed spindles, servo motors, CNC machine tools, robotics, wind turbines, and radar systems. These encoders are primarily used for the purpose of positioning and speed control. However, it is worth mentioning that the encoder signal also carries rich information about the health condition of rotating machinery, thus having a great potential to be used for diagnosis and prognosis. Compared with the traditional vibration analysis, the encoder-based scheme has several major advantages. First, since the encoder is directly connected to the rotating shaft, the encoder signal can truly reflect the dynamic behavior of machinery. Second, due to the short transfer path, the signal to noise ratio (SNR) of encoder signal is relatively high, and thus is more sensitive to incipient and early faults. Third, as encoders have already been built into rotating machinery, the dynamic signal of machinery can be directly accessed without further investment on sensors and acquisition hardware. Therefore, it can be considered as a zero-cost measurement scheme. By making full use of those built-in encoders, it is also expected to develop some smart machinery with capability of self-awareness and self-diagnosis. Thanks to the above advantages, the encoder based diagnosis and prognosis, commonly achieved by analyzing the instantaneous angular speed (IAS) of machinery [3–5], have drawn increasing attention in recent years. It is basically applicable to different rotating components/machines, such as gearbox [6], bearings [7,8], electric motors [9,10], high-speed spindles [11], aircraft propeller [12] and engines [13,14].

Although some prior research work has been carried out in this field, the feasibility of employing encoder signal for condition monitoring and fault diagnosis of planetary gearbox has not been investigated yet. As a critical transmission component, planetary gearboxes are widely used in automotive, mine excavator [15], helicopters [16], aerospace and wind turbines [17–20], etc. Despite the wide use and long application history, the monitoring and diagnosis of planetary gearboxes are still commonly achieved by vibration analysis [21,22]. When vibration-based techniques are employed, several major challenges are inevitable [23]. First, since the vibration sensor is typically mounted on gearbox casing, the vibration transfer paths for different planet gears are distinct. For this reason, the measured signal is actually the non-linear superposition of the vibration from each planet gear, which poses difficulties for signal analysis and interpretation. Moreover, the meshing locations of both the planet–ring and planet–sun gear pairs change with the rotation of planet carrier, thus resulting in extra amplitude modulation to the measured signal and making spectral structure more complicated [24]. In addition, due to the long propagation path and large inertia, the fault vibration response on the casing is relatively weak, therefore it can easily be masked by measurement noise and other interferences.

In fact, the above mentioned limitations of vibration based method are expected to be alleviated if encoder-based scheme is employed. The present study aims to demonstrate this feasibility and further provide a methodology for the diagnosis of planetary gearboxes using encoder signal. The rest of this article is organized as follows. The principle and measurement of encoder signal are described in Section 2. To convert the raw encoder signal into more meaningful and interpretable speed information, a Kurtosis-guided local polynomial differentiator (KLPD) is proposed to estimate the instantaneous angular speed (IAS) of a planetary gearbox. The principle, implementation as well as performance analysis of KLPD are also elaborated in Section 3. In order to remove the operation-related IAS components that come from normal gear meshing and load variation, an IAS model for planetary gearbox is presented in Section 4. Based on this model, a residual extraction scheme is proposed to enhance the weak speed jitters caused by gear defect. The effectiveness of proposed method is validated by the encoder signal measured from an industrial planetary gearbox with different types of faults in Section 5. Finally, conclusions are drawn in Section 6.

2. Principle and measurement of encoder signal

Rotary encoder, also called shaft encoder, is a device that measures the angular position or motion of a shaft. The basic construction of an optical rotary encoder is illustrated in Fig. 1(a). A beam of light emitted from an LED passes through a grating with N equally spaced slits. When encoder rotates with shaft, cyclical light intensity change is picked up by a photodiode array, which further converts these variations into voltage signals. The typical output of a rotary encoder is TTL (Transistor-Transistor Logic) square waves as shown in Fig. 1(b), with each period corresponding to a slit on the disk. The angular position of shaft can be determined by counting the elapsed periods of TTL.

Although TTL encoder allows to count how many slits has been rotated, it is still difficult to identify the accurate location between two adjacent slits according to the measured voltage (See the sampling point denoted by **S** in Fig. 1(b)). It is due to the fact that TTL waveform provides only two constant voltage levels within each period. For this reason, the TTL encoder may not meet the angular resolution requirements in high-precision IAS estimation or speed control. To address this issue, sine-wave encoders (SWE) are developed and widely used in recent years [25]. Different from TTL encoder, SWE generates two quadrature sine waves as illustrated in Fig. 1(c). They are called A-phase and B-phase respectively, which are phase shifted by 90°.

For any sampling point **S**, once its A-phase voltage A_s and B-phase voltage B_s are measured, the exact location of **S** between two adjacent slits can be identified by arctangent operation, i.e., $\varphi = \arctan(A_s/B_s)$. It means arbitrary levels of angular resolution can be achieved in theory using this kind of output. In addition, according to the phase relationship, one can also determine the direction of motion. Specifically, if A leads B by 90°, the shaft is rotating in clockwise direction, and vice versa.