Experimental investigation of sensor mounting positions for localized faults detection of epicyclic gear sets

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Abstract

In the literature reports on the vibration based localized faults detection of epicyclic gear sets, the vibration sensor is often mounted on the ring gear or the housing adjacent to the ring gear. However, this sensor mounting position is often too ideal to be utilized in applications. There are different structures of epicyclic gear sets widely used. It is a challenge for selecting a suitable sensor mounting position. In this paper, the sensor mounted on the input/output shaft bearing house for picking up the vibration is experimental investigated, and compared with that from the conventional sensor mounting position. Analysis results shown that the bearing house position can also be employed to expose the fault features of planet gears.

1 Introduction

Planetary gearboxes as important rotating mechanical transmission units are widely used in the wind turbines, helicopter, automobiles, and marine vehicles. However, due to rigorous working conditions in applications, and the wear and crack failures of planetary gear sets occurred frequently [1]. Therefore, the condition monitoring and faults diagnose of planetary gear sets become more and more important.

Compared with the vibration picked up from a fixed-axis gearbox, the vibration picked up from a planetary gearbox are more complicated. In a conventional single-stage planetary gearbox, several planet gears rotate around the sun gear and rotate around their own centers simultaneously, and each planet gear meshes with the sun gear and the ring gear at the same time. On the other hand, the epicyclic motions of planet gears make the mesh positions changed from time to time, which cause the vibration transfer paths between the gear mesh positions and the fix-mounted sensor position are time-varying. As a result, rich modulation phenomena can be observed in the picked up vibration from a planetary gearbox.

As well known that picking vibration is one of important steps in the condition monitoring and faults diagnosis. Generally, it is expected that the picked vibrations contain more significant fault features, which can reduce the requirement to the following signal processing procedures. Then, the sensor mounting position should be considered carefully at first. However, the sensor mounting position of the planetary gearbox is few discussed by literature. In most theoretical literature experimental studies, vibration sensors are often mounted on the ring gear or the housing adjacent to the ring gear [1-3]. However, this sensor mounting position is too ideal to be utilized in applications. Due to different structures of epicyclic gear sets. To some structures, e.g. the ring gear is rotating, the ring gear position is impossible to mount the sensor at all. It is a challenge for the vibration analysis based condition monitoring and faults diagnosis. In addition, part of the research is based on mounting the sensor inside the planetary gearbox for fault diagnosis. For example, mount the sensor on the planet carrier [4,5]. For the built-in sensor installation method, the sensor installation space in a planetary gearbox should be considered firstly, which will put forward new requirements on the design, manufacture and disassembly for the planetary gearbox. In other word, this method has no universal applicability. On the other hand, similar to the sensor installation method for the fixed-axis gearbox picking up the vibration, which mounted the sensor on the input/output shaft bearing housing, should be a feasible sensor mounting position for planetary gearboxes. However, this mounting position has a problem that the vibration transfer path between the mesh point of the ring-plant gear pairs and the sensor is much longer comparing with the conventional ring gear related sensor mounting position. It is worth carrying out an investigation on the different sensor mounting positions for applications of the condition monitoring and faults diagnosis of planetary gearboxes. To address this issue, an experimental investigation has been carried out on a planetary gearbox test rig for the vibration based tooth-root crack faults detection. The well-known vibration separation technique and the synchronous averaging are utilized to extract the faults characteristics through the vibration picked up from different sensor mounting positions for a comparison. Experimental results show that the fault features contained in the observed vibration from bearing housing are weaker than that obtained from ring gear position. However, the bearing housing sensor mounting can also be utilized for the vibration based tooth faults detection by using the vibration separation and the synchronous averaging.

2 Planetary Gearbox Transmission

As shown in Fig. 1, a single-stage planetary gearbox is generally composed of a sun gear, several planet gears, a ring gear and a planet carrier [6]. Different from the conventional fixed-axis gearbox, the vibration transfer paths between the sensor and the meshing points are time-varying under the running condition of the planetary gearbox. Three structures of epicyclic gear sets commonly used are shown in Figs. 2(a)-(c), which correspond to the planetary gear set with the standstill ring gear, with the standstill sun gear, with the rotating sun gear and the rotating ring gear, respectively [7].

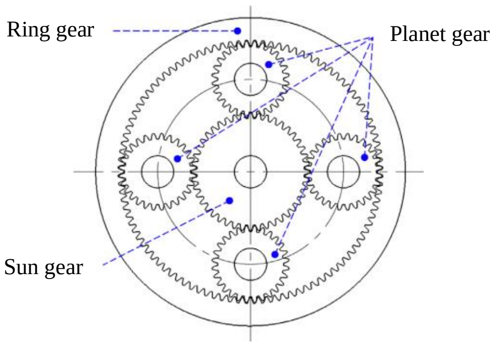

Figure 1: A planetary gear set with 4 planet gears.

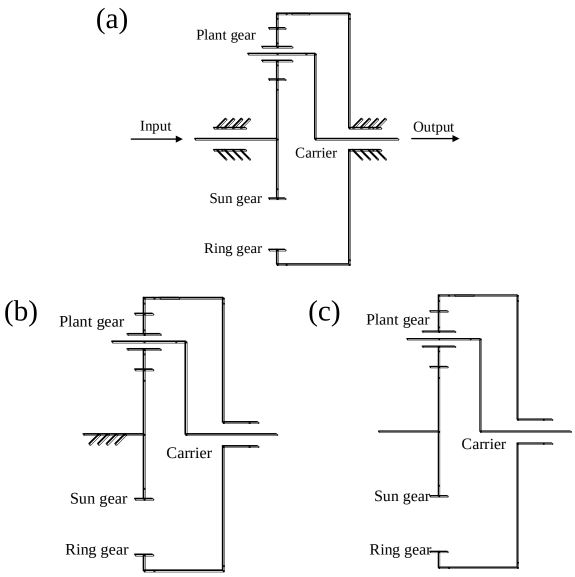

Figure 2 : Structures of planetary gear sets with: (a) standstill ring gear, (b) standstill sun gear, (c) rotating sun and ring gears

In literature reports of the vibration analysis of planetary gear sets, the sensor mounting position is often based on the structure with a standstill ring gear shown in Fig. 2(a). It is noted that the ring gears can also be rotating as the structures shown in Figs. 2(b) and (c), which rise challenges for selecting a suitable sensor mounting position. As well-known that the bearing housing utilized as the sensor mounting position for a fixed-axis gearbox is widely adopted in applications. However, the bearing housing sensor mounting for the vibration analysis of planetary gear sets is still an issue. It has two obviously drawbacks. Firstly, the vibration transfer path is much longer than that of the sensor mounted on the ring gear. Secondly, the interferences from adjacent bearings can lead the picked vibration much noisy. Then, the bearing housing sensor mounting is few reported in the literature. However, the bearing housing sensor mounting can be implemented in most applications of epicyclic gear sets. Then, it is worth investigating whether the bearing housing sensor mounting position is suit for the faults detection of epicyclic gear sets.

In this paper, experimental studies and vibration analysis for the planetary gearbox test rig with a tooth-crack of a planet gear have been carried out based on the vibration picked up by sensor 2 and 3 at the sensor mounting positions shown in Fig. 3, respectively.

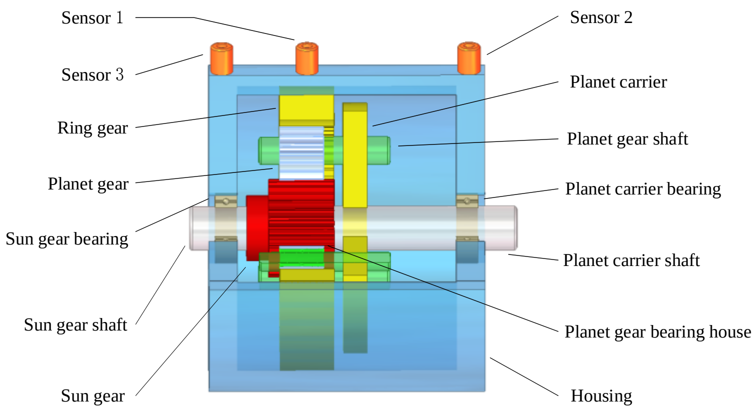

Figure 3: Installation location of sensors.

3 Briefs on Vibration Separation and the Synchronous Averaging

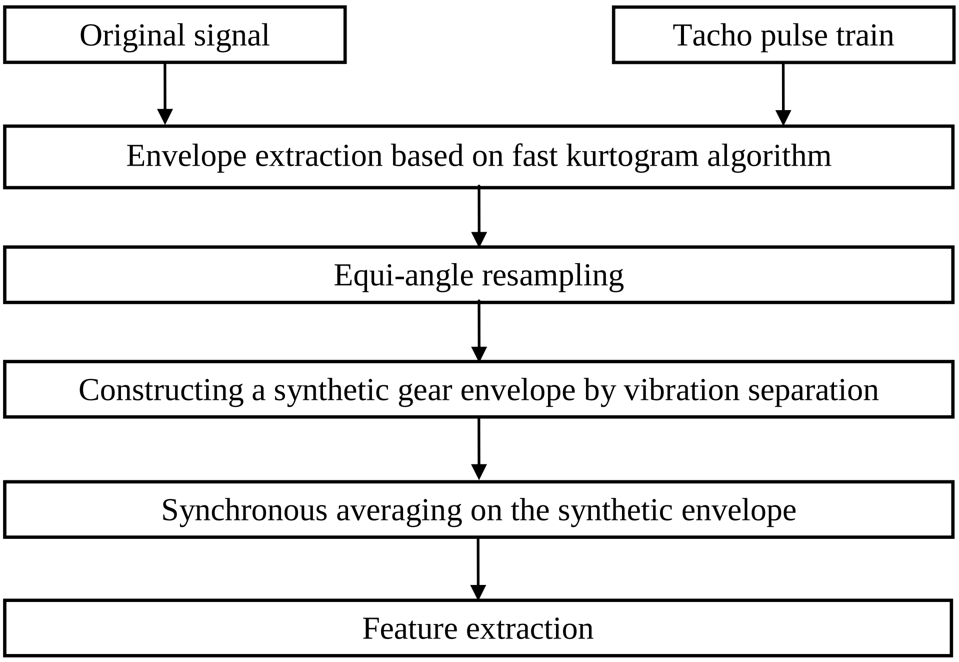

Figure 4 : Brief description of the method flow

As mentioned above, the vibration transfer path between the tooth mesh position and the sensor is time-varying under the condition that the sensor is mounted on the ring gear or the housing adjacent to the ring gear. It is worth mentioning that even though the length of vibration transfer paths seem to be a constant under the condition that the sensor is mounted on the input/output shaft bearing house, the vibration picked up by the sensor is also time-varying. The reason is that the changes of the meshing positions of planet gears make the picked vibration on the bearing house acting as a rotating vector. Therefore, the vibration separation [8,9] and the synchronous averaging [8] should be employed to eliminate the effects from the time-varying vibration transfer path. To extract the weak fault features of planetary gear sets, a combination scheme of envelope extraction, vibration separation and synchronous averaging has been proposed in [6] for the fault diagnosis of planetary gear sets recently. In this scheme, the envelope is demodulated to make the weak impulsive localized fault feature of the planetary gear sets prominent, the well-known vibration separation is utilized to eliminate the influence of time-varying transfer path, and the angular-domain synchronous averaging is used to reduce the influence of speed fluctuation and improve the signal-noise ratio (SNR). The schematic of the envelope-windowed vibration separation is shown in Fig. 4. The main steps are listed as follows [6].

(1) *Envelope extraction*. The fast kurtogram algorithm [10] is employed to extract the complex envelope from a maximum spectral kurtosis value determined demodulation frequency band.

(2) *Equi-angle resampling on the envelope*. Performing the equi-angle resampling scheme on the imaginary and the real parts of the complex envelope in the time domain, the complex envelope in the angular domain can be obtained.

(3) *Constructing a synthetic gear envelope by vibration separation*. The vibration separation technique is applied on the envelope in the angular domain. Then, a synthetic envelope is constructed according to the teeth mesh sequence of the interesting gear.

(4) *Synchronous averaging on the separated envelope.* The synchronous averaging is utilized on the synthetic envelope to remove the non-synchronous components.

(5) *Feature extraction*. The order envelope spectrum is calculated by the Fast Fourier Transform (FFT). Then, the fault feature can be exposed.

More details on the scheme of envelope windowed vibration separation and synchronous averaging can be found in [6].

4 Feature Frequencies of Planetary Gear Sets

Understanding the feature frequencies or orders of planetary gear sets is the core in the condition monitoring and faults diagnosis, by which we can explain the frequency lines in a spectrum reasonably and make a decision on the health status of the planetary gear set. Assuming f_c denotes the rotation frequency of the carrier, the meshing frequency f_m can be given as in [9] by

$$f_m = N_r f_c = N_p(f_p + f_c) = N_s(f_s - f_c) \tag{1}$$

where N_r is the teeth number of the ring gear, N_p is the teeth number of the planet gear, N_s is the teeth number of the sun gear, f_p denotes the absolute rotation frequency of the planet gear, and f_s represents the absolute rotation frequency of the sun gear. Using the carrier as the reference, the corresponding meshing order l_m can be calculated by

$$l_m = \frac{60 f_m}{n_c} = \frac{60 N_r f_c}{60 f_c} = N_r \tag{2}$$

where n_c is the carrier speed. The feature frequency of the planet gear with a tooth-root crack f_p^r is the rotation frequency of planet gear relative to the planet carrier, which is expressed as in [9] by

$$f_p^r = f_p + f_c = f_c(N_r / N_p) \tag{3}$$

And the feature order of the planet gear with a tooth-root crack can be given by

$$l_p^r = \frac{60 f_p^r}{n_c} = \frac{60 f_c (N_r / N_p)}{60 f_c} = N_r / N_p \tag{4}$$

5 Experimental verification

5.1 Experimental description

In the investigation, the experiments have been carried out on a planetary gearbox test rig for the vibration based tooth-root crack faults detection. The test rig is a 75 kW transmission system, which is driven by an AC drive motor with an adjustable speed range from 0 to 2500 rpm. The loading unit is an AC induction generator in tandem with a digital AC drive to regenerate the power back into the system. The test unit is a single-stage planetary gearbox (type: NGW 2K-H) as shown in Fig. 5 with the specific parameters listed in Table 1. The DH904 eddy current sensor is mounted on position 1 shown in Fig. 5 for picking up the tacho pulse train. Three DH112 acceleration sensors are mounted at positions 2, 3, and 4 respectively for picking up the vibrations from the planetary gearbox. A NI 9234 4-channel card is used for the data acquisition with sampling rate 51.2 kHz. It is worth mentioning that the planet carrier shaft is the input and the sun gear shaft is the output. The position 2 is on the sun gear bearing housing, the position 3 is on the housing adjacent to the ring gear, and the position 4 is on the planet carrier bearing housing. The data series used in this study are the vibrations picked up at positions 2 and 3 respectively. And the tacho pulse train is obtained by the eddy current sensor at position 1. In order to simulate the tooth-root crack fault of a planetary gear, a crack of about 4 mm is machined at the tooth root of a planetary gear by the wire cutting method as shown in Fig. 6.

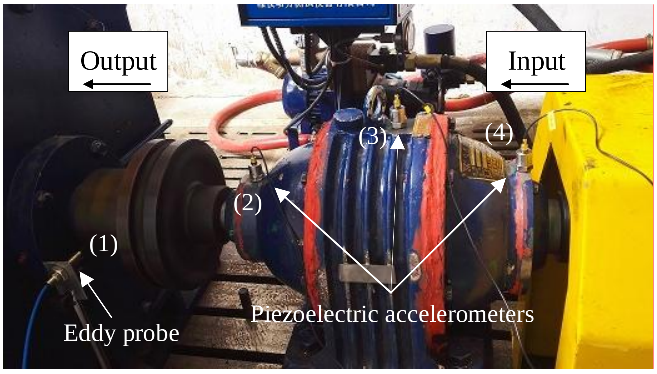

Figure 5 : Test rig of planetary gear transmission

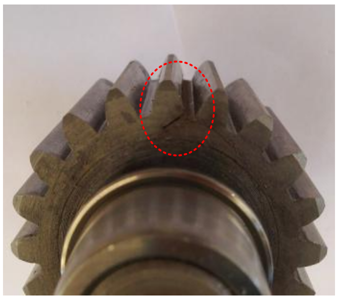

Figure 6 : Planet gear with tooth root crack

Gear	Sun gear	Planet gear	Ring gear
Number of teeth	28	20	71

Table 1: Parameters of planetary gearbox

In the experiment, the rotation speed of the input shaft is at about 1000 rpm. The characteristic orders of the planetary gear in the planetary gearbox can be calculated by Eqs. (2) and (4) in theory, which are listed in Table 2 by using the planet carrier as the reference.

Planetary gearbox meshing order l_m	71.00 ×
Planetary fault order l_p^r	3.55 ×
Planetary carrier frequency order l_c	1.00 ×
Planetary frequency frequency order l_p	2.55 ×

Table 2 : Characteristic orders of the planetary gearbox

5.2 Experimental data analysis

The waveforms in of the raw vibration picked up by the sensors mounted at positions 2 and 3 are shown in Figs. 7 and 8, respectively. The tacho pulse train obtained by the eddy probe at position 1 and the corresponding speed curve are shown in Figs. 9 and 10.

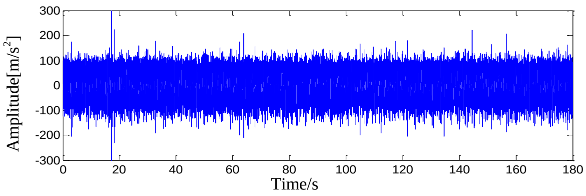

Figure 7 : Vibration waveform observed at position 2

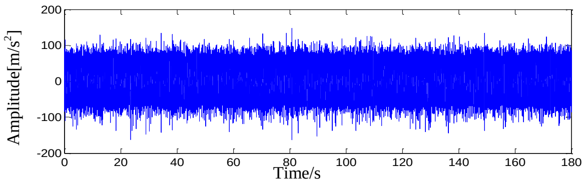

Figure 8: Vibration waveform observed at position 3

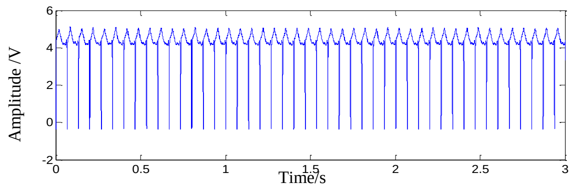

Figure 9: Speed pulse

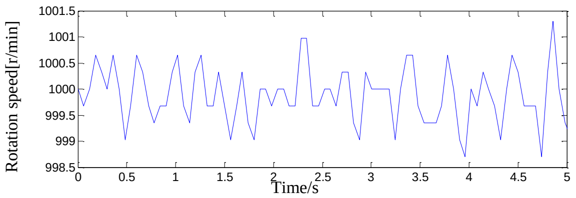

Figure 10 : Speed curve

Using the vibration separation and the synchronous averaging techniques, the order spectra of the vibrations picked up at the positions 2 and 3 are shown in Fig. 11, where the characteristic order (3.55×) and its harmonics related to the tooth-root crack of a planet gear order are exposed clearly. Experimental results show that the fault feature contained in the observed vibration from the bearing housing (position 2) is weaker than that obtained from the ring gear position (position 3). However, it is worth noting that the bearing housing sensor mounting position can also be utilized for the vibration based tooth faults detection by using the vibration separation and the synchronous averaging techniques.

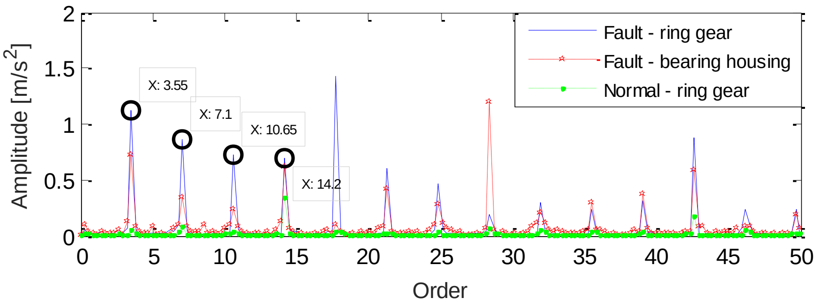

Figure 11 : Fault characteristic order of planet gear fault

6 Conclusion

In practical applications, different structures of epicyclical gear sets widely used. According to a specific structure of a planetary gear set, the sensors should be mounted on suitable positions to pick up vibration. The experimental investigation results show that the sensors mounted on the position of the bearing housing and mounted on the housing adjacent to the ring gear both can be utilized for the vibration based tooth faults detection by using the vibration separation and the synchronous averaging techniques. Moreover, the experimental results also show that the bearing housing sensor mounting position is also can be employed for the faults detection of planetary gear sets, but the fault feature is weaker than that obtained from ring gear position.

Acknowledgments

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