School of Mechanical and Manufacturing Engineering

Faculty of Engineering

The University of New South Wales

Vibration Diagnosis of Planetary Gearbox under Variable Speed Condition

by

Hengcheng Zhang

Thesis submitted as a requirement for the degree of

Master of Engineering in Mechanical Engineering

Submitted: October 2017 Student ID: z5130844

Supervisor: A/Prof.Z.Peng Dr.W.Smith Topic ID:

Abstract

Acknowledgements

Abbreviations

BE Bachelor of Engineering

LaTeX A document preparation computer program

PhD Doctor of Philosophy

Contents

1 Introduction **1**

2 Literature Review **2**

2.1 Planetary gearbox 2

2.2 Planetary Gearbox fault diagnosis 3

2.2.1 Vibration generated by gear 4

2.2.2 Diagnosis techniques 6

2.3 Variable Speed 10

3 Methodology **11**

4 Results and Discussion **12**

4.1 Results 12

4.2 Discussion 12

5 Conclusion **13**

5.1 Future Work 13

Bibliography **14**

Appendix 1 **16**

Appendix 2 **17**

B.1 Data 17

List of Figures

2.1 Planetary Gearbox Layout[2] 3

2.2 Time Synchronous Averaged signals [11] 8

2.3 Demodulation of the second harmonic of the gearmesh frequency for a cracked gear [13] 9

List of Tables

Chapter 1

Introduction

The aim of this article is to investigate a method to identify planetary gearbox fault by vibration analysis. The planetary gearbox is

Chapter 2 explains the background for this document.

Chapter 3 explains content related requirements to theses. Chapter 4 evaluates the thesis requirements template. Finally, Chapter 5 draws up conclusions and suggest ways to further improve the thesis requirements template.

Chapter 2

Literature Review

In this chapter, some basic concepts and important knowledge are provided. These concepts are

2.1 Planetary gearbox

Planetary gearing or epicyclic gearing is a gear system typically consisting of four parts: sun gear, planet gear, ring gear and the planet carrier.

There are several ways of input-output method such as stationary ring gear, fixed carrier or no stationary part. The gear ratio of the planetary gearbox could be calculated as:

$$N_s\omega_s + N_p\omega_p - (N_s + N_p)\omega_c = 0 \tag{2.1}$$

$$N_r\omega_r - N_p\omega_p - (N_r - N_p)\omega_c = 0 \tag{2.2}$$

The following figure shows a typical planetary gearing system, which contains 3 planet gears.

The characters of planetary gearbox make it suitable for large transmission ratio, high load and split input or output circumstances. So it is widely used in wind turbines,

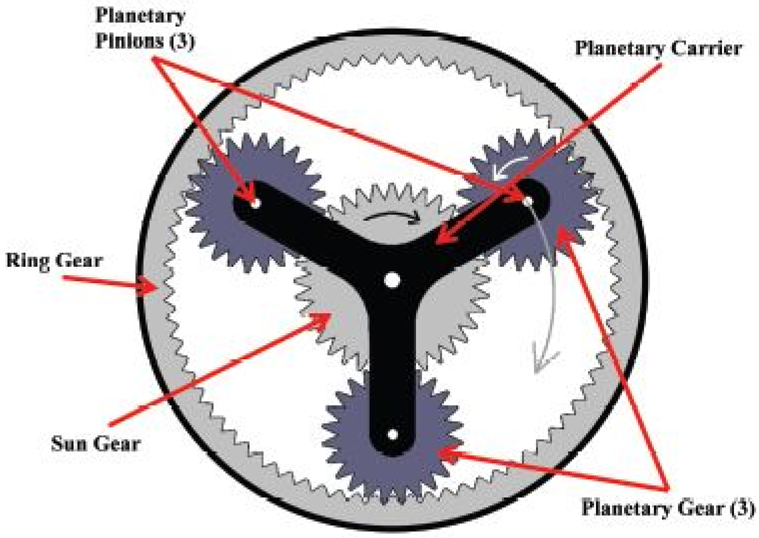

Figure 2.1: Planetary Gearbox Layout[2]

lathes, automobiles and helicopters. The widely appliance and tough working environment of planetary gearbox require it to be highly dependable. Failures of planetary gearbox may lead to huge economic losses as well as safety incidents. But the compact and complex structure on the other hand make it difficult to monitor its condition. Especially when the load and operating speed are varying. This project focuses on the varying speed conditions.

2.2 Planetary Gearbox fault diagnosis

Vibration of gear is caused by the geometric deviation of gears and teeth deformation under load. These two effects introduce a 'meshing error' or 'transmission error' (TE). [3]The transmission error could be divided into three types: unloaded static TE, loaded static TE and dynamic TE. The unloaded static TE could be measured under a very light load, and it is realised to be caused by the geometric deviation. The load static TE is introduced by the tooth deflection under a constant load torque. Dynamic TE is caused by the fluctuation of torque and transmission speed.

2.2.1 Vibration generated by gear

Based on the understanding of transmission error, vibration generated by gears is classified as follows: [3]

1) Mean effects for all tooth pairs

The mean effects here are the same for all tooth pairs. Torque varies when each pair of teeth mesh and cause vibration. Therefore it is dominated by harmonics of tooth-mesh frequencies. It could be sub divided into tree parts:

- Tooth deflection due to mean torque.
- The mean part of initial profile errors resulting from manufacturing.
- Uniform wear over all teeth.

Uniform wear of teeth could increase friction force, which would results in higher harmonics of the gearmesh frequency.

2) Variation from the mean.

Variation from the mean could give rise to side bands of harmonics and maybe caused by:

- Slow variations, such as distortion and runout.
- Local faults, such as tooth spalls and root cracks.
- Random errors.
- Systematic erros.

Sidebands around the harmonics of gearmesh frequencies contain the gear fault information. The spaces between sidebands and harmonics shows which gear has fault, while the form of sidebands identify the type of fault. For example, local faults may give rise to a flat sideband spectrum, while distributed fault may inspire higher level but narrowly grouped sidebands. Due to limitation of time and resource, the main fault investigated in this project is Local fault, including tooth spalls and root cracks. Separation of spalls and cracks is another important topic due to the reason that cracks could cause a much more rapid failure. Endo[6] developed a finite element analysis method to investigate their difference. It was found that cracks at tooth root give a two-stage deviation of transmission error due to the reason that at first stage, faulty tooth together with a healthy tooth share the load and at the second stage, faulty tooth stands the load alone. Spalls on the other hand inspire one deviation of TE when mating tooth pass the spall.

Comparing to fixed-axis gearbox, in which each gear rotates around a fixed centre, planetary gearbox has planet gears which rotate around not only their own centres but also the centre of sun gear. The transmission structure of planetary gearbox bring unique behaviours. [4]

1. The planet gears are meshing simultaneously with sun gear and the ring gear. Part of the vibrations exited by different component and their different meshing phases could be neutralized or cancelled by each other.

2. The multiple vibration transmission paths are time-varing and load effected in planetary gearbox.It could attenuate the vibration signal of defective part and weaken the fault characteristics.

3. Differ from fixed-axis gear box, side bands apear in spectrum for both healthy and faulty planetary gearboxes and asymmetric about the tooth-mesh frequency. It may caused by multiple planet gears meshing with different phases.

4. Vibrations of low speed faulty components are easily masked and difficult to discover.

2.2.2 Diagnosis techniques

As discussed in the former section, when gears are operating in good condition, the vibration signal tend to be stationary, containing gearmesh frequency and shafts rotating frequencies. When fault happens, the amplitude or frequency components change according to the fault types. Plenty of diagnosis techniques are developed to seperate the faulty information from the original signal. [7]

Statistic Indicators

Time domain statistical indicators are carried out directly from the vibration signal. Some of them are scaled including peak value, peak to peak value, mean value, root mean squared value and variance. Among which RMS (root mean squared) value, as its name suggests, is the root of the mean of the squared signal values. It represents the overall vibration level. It is calculated as:

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{n} x_i^2} \tag{2.3}$$

Variance indicates the power of the vibration, and its formula is:

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{n}(x_i - \overline{x})^2 \tag{2.4}$$

There are also some useful unscaled indicators, including kurtosis, crest factor and pulse factor. Kurtosis is the fourth moment normalised by the square of the mean square of the vibration signal waveform and represents the amplitude of impulse energy. [8]

$$K = \frac{\frac{1}{N}\sum_{i=1}^{n}(x_i - \overline{x})^4}{RMS^4} \tag{2.5}$$

Crest factor shows impulse energy in another form:

$$C = \frac{x_{peak}}{RMS} \tag{2.6}$$

Scaled indicators not only depend on the condition of the machine but also its running speed and load. Unscaled indicators have the benefit that they are independent of the running status.

Time Synchronous Averaging

TSA (Time synchronous averaging) is also atime domain signal processing method other than statistical indicators. It is implemented by averaging several segments of synchronousing signals together to extract the periodic signal from the backgound noises. It is calculated by:

$$y_a(t) = \frac{1}{N}\sum_{n=0}^{N-1} y(t+nT) \tag{2.7}$$

The implementation of TSA depend on the corresponding of sample signals. Which means to be averaged numbers at each point should have the same rotating phase. This is guaranteed by 'Order traking' method. When analysing vibration signals of the rotating machines, a slight fluctuation of the rotating speed could cause smearing of the frequecy components. Order tracking is taking use of a shaft encoder signal or a tacho signal to resample the original signals with constant time interval into constant phase intervaled signal. This method make sure that the samples have same number and starting phase during each revolution. It is recomment to always perform order tracking before implementing TSA even at a constant speed.

The TSA method is firstly introduced into gear fault diagnosis by Stewart [9], whose propose to abtain the residual signal by removing the periodic gearmeshing pattern, and use the kurtosis of the residual signal as the fault indicator. Peter McFadden [10] enhanced this method by improvements of the TSA as well as order tracking operations. He proposed to select short section of signals which correspond to the vibration of one tooth and assembly together to the whole gear. Taking twice length of toothmesh period signal sections with Hanning window was recommended to improve the frequency spectra in his later papers. [12] Time synchronous averaged signals for a fixed period, normally one or two rotation of the shaft, would illustrate the fault type

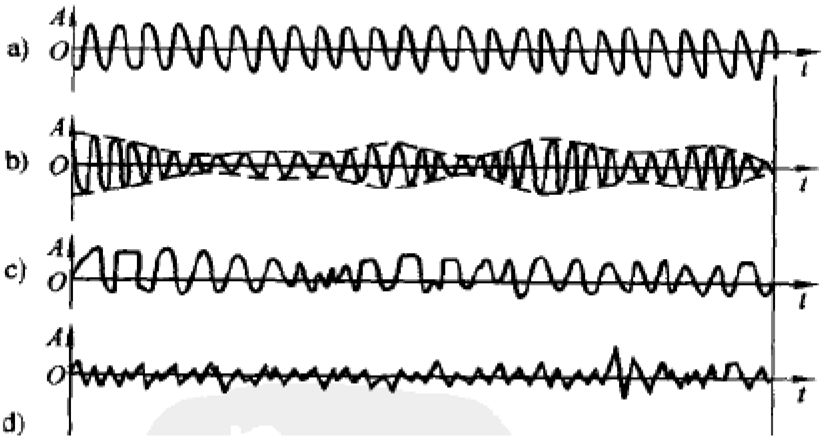

Figure 2.2: Time Synchronous Averaged signals [11]

of the gear. As shown in Figure 2.2, plot a) is a steady gearmesh vibration. In plot b), the signal is amplitude modulated, which maybe a consequence of misalignment. Plot c) is possibly because of significant wear of teeth surface, and plot d) may caused by cracked tooth.

Frequency-domain Methods

Time-domain methods such as statistical indicators is able to find whether the gear is in malfunction, but not sufficient to the fault type.Frequency-domain methods are more capable of this requirement. They are developed based on Fourier transform. Under normal operating condition, the spectrum is domained by shaft rotating and gearmesh frequency. Sidebands around them and their harmonics would identify the type of fault in some content as discussed in chapter 2.2.1. Further than Fourier transform or its implementation for digital signal, DFT and FFT, demodulation techniques and cepstrum analysis are utilized to run the diagnosis.

As already known that the faulty information of gears ususally hide in the sidebands around gearmesh frequency and its harmonics, and these sidebands are mostly caused by amplitude and frequency modulation. Demodulation techniques such as Hilbert transform are effective to carry out the modulation signal. Thus it is able to investigate

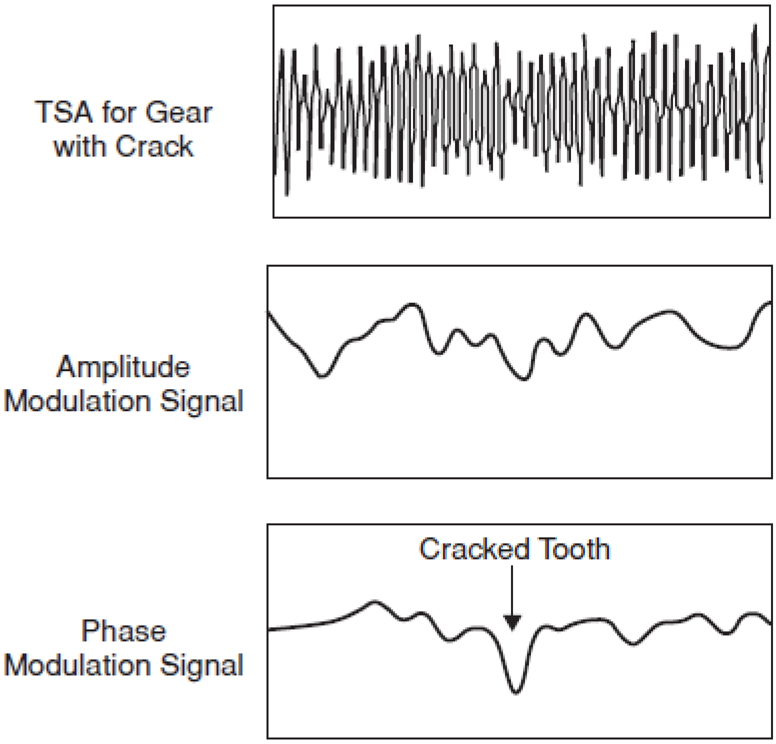

Figure 2.3: Demodulation of the second harmonic of the gearmesh frequency for a cracked gear [13]

their faulty type and damage extent. One example is introduced in [13]. It use Hilbert transform to demodulate the second harmonic of gearmsh frequency of the TSA signal. As seen in Figure 2.3, the phase modulation signal of the TSA signal clearly shows the cracked tooth. It is even able to be known which tooth is in fault with certain phase information.

Cepstrum analysis is another important method to investigate the sidebands and transfer function. Cepstrum is the inverse Fourier transform of a logarithmic spectrum, which is Fourier transformed from a time signal. It is then:

$$\hat{x}(\tau) = IF[log(X(f))] \tag{2.8}$$

Where $X(f)$ is the spectrum signal.

Time-frequency-domain Methods

Time-frequency domain methods is a combination of time and frequecy domains in one plot. Methods such as Wigner-Ville distribution and wavelets analysis are studied recently as another choice in vibration diagnositics. Meltzer *et al.* [15] [16] conducted this method on an automobile planetary gearbox.

Other Methods

Some other effective methods exist in this area, for example modeling method and intelligent method.

...

2.3 Variable Speed

Most of the methods mentioned in the former part are developed for constant speed and load conditions. When there are minor speed fluctuations, performing of order tracking would eliminate this effect. But when it comes to wider speed range, as much as $\pm$ 30 percent. Besides frequency modulation, amplitude modulation caused by passage of resonances, frequency response function and variation of torque due to speed comes into consideration. These effects can not be compensated by order tracking. Residual signal of TSA under these conditions would include much of the amplitude variation of the deterministic part as well as the random noise. [14]

Chapter 3

Methodology

Chapter 4

Results and Discussion

This chapter is mainly provided for the purpose of showing a typical thesis structure. There are no more thesis requirements described.

4.1 Results

The result of this work is the present document, being both a LaTeX template and a thesis requirement specification.

4.2 Discussion

The Dual function of this document somewhat de-emphasises the primary purpose of the document, namely the thesis requirements. It would be better, if these could be stated on a few concise pages (cf Appendix 1, p16).

Chapter 5

Conclusion

A thesis requirements/template document has been created. This serves the dual purposes of giving students specific requirements to their theses — both style and content related — while providing a typical thesis structure in a LaTeX template.

5.1 Future Work

Extract the requirements from the template in order to have very concise requirements.

Bibliography

[1] H. Partl:*German TEX*,TUGboat Volume 9, Issue 1 (1988)

[2] National Research Council, *Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles*,(2015)

[3] Robert Bond Randall,*Vibration-based Condition Monitoring - Industrial, Aerospace and Automotive Applications*, (2011)

[4] Yaguo Lei, Jing Lin, *Condition monitoring and fault diagnosis of planetary gearboxes: A review*, Measurement, vol. 48, Feb. 2014

[5] P.D.McFadden, I.M.Howard, *The detection of seeded faults in an epicyclic gearbox by signal averaging the vibration*, Aeronautical Research Labs Melbourne, 1990

[6] Endo, H. Randall, R.B. *Differential diagnosis of spalls vs. cracks in the gear tooth fillet region* Journal of Failure Analysis and Prevention, 4(5), 57-65

[7] K. Ding, *Practical Fault Diagnosis Techniques for Gears and Gearboxes* , 2005

[8] W. S. Siew, W. A. Smith, Z. Peng, and R. B. Randall, *Fault Severity Trending In Rolling Element Bearings*, presented at the Acoustics 2015 Hunter Valley, 2015.

[9] R.M.Stewart, *Some useful data analysis techniques for gearbox diagnostics*, Proceedings of the Meeting on the Applications of Time series Analysis, ISVR, University of Southampton

[10] P.D.McFadden,*A technique for calculating the time domain averages of the vibration fo the individual planet gears and the sun gear in an epicyclic gearbox*, Journal of Sound and Vibration,144(1), 163-172.

[11] Kexing Chen, *Mechine Condition Monitoring and Fault Diagnosis Technology*, Beijing Science and Technology Press, 1991

[12] P.D.McFadden,*Windo functions for the calculation of the time domain averages of the vibration of the individual planet gears and sun gear in an epicyclic gearbox*, ASME Transactions Journal of Vibration, Acoustics,**116** 179-187.

[13] P.D.McFadden,*Detecting fatigue cracks in gears by amplitude and phase demodulation of the meshing vibration*, ASME Transactions Journal of Vibration, Acoustics, Stress and Reliability in Design **108**, 165-170.

[14] R.Randall, M.Coats, W.Smith *Gear diagnostics under widely varying speed conditons*, School of Mechanical and Manufacturing Engineering, University of New South Wales, Australia

[15] 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

[16] 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

Appendix 1

This section contains the options for the UNSW thesis class; and layout specifications used by this thesis.

Appendix 2

This section contains scads of supplimentary data.

B.1 Data