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Fatigue Prediction of a Gear Transmission System based on Vibro-Acoustic Measurements

Anwar Ahmaida, Dong Zhen, Fengshou Gu and Andrew Ball
University of Huddersfield, Queensgate, Huddersfield HD1 3DH, UK

ABSTRACT

Gearing components play a pivotal role in most power transmission mechanisms but their application in industry consistently results in significant disruption and losses due to gear failures. This emphasises the significance of condition monitoring and fault diagnostics techniques of gear transmission systems to enhance overall safety and operational reliability in order to minimise gearbox failure rates and their associated disruption and losses to industry. In a wide range of industrial contexts, vibration analysis is extensively used for machinery condition monitoring and diagnostics due to its good detection results. As vibration and acoustic noise have the same generation mechanism, acoustic noise can also be used for machinery condition monitoring combined with effective signal processing methods. In this paper, vibration and acoustic signals were both used to analyse the fatigue process of a gear transmission system based on synchronous vibro-acoustic measurements. In order to enhance the signal-to-noise ratio (SNR) of the measured signals, time synchronous average (TSA) technique was employed to pre-process the vibration and acoustic signals. The side band energy ratio (SER) is then extracted to predict the vibration and acoustic signals to indicate the fatigue process of the testing gearbox under different operating conditions. Further the fatigue process was detected through analysing the measured signals in the high frequency band as these are less contaminated by background reverberation interferences. The key results show that the gear transmission system can be monitored by vibration and acoustic analysis which show similar trend results for the gear fatigue process tested.

Keywords gearbox, vibration, acoustic, fatigue analysis

INTRODUCTION

Gears have long been used as a means of power transmission in many industrial applications such as terrestrial gearboxes and power generators [1]. Their function is to accomplish a change of speed which is usually rotational. Gearboxes essentially consist of a set, or sets, of gears mounted on shafts and supported by bearings, with the entire system enclosed and supported within housing and lubricated. An electric motor power source drives the gearbox input shaft, normally at a relatively high speed. Internally the gears transmit a reduced speed to the output shaft resulting in an increase in output torque [2].

Vibration signals are the principle means of gearbox condition monitoring as they provide the easiest method to gather and reflect the basic excitation motion of the gearbox. Additionally airborne acoustics or noise, being correlated closely to vibration but measured with more comprehensive information in a remote way, has also been actively investigated for condition monitoring and fault diagnosis of gearboxes in the last two decades. Nevertheless, both vibration and acoustic signals can be contaminated by different noises and careful analysis with more advanced tools should be carried out to obtain reliable features for fault diagnosis. Conventional methods of monitoring vibration are based on the assumption that the deterioration in the condition of a gearbox may be detected by changes in the measured structural response (vibration signal) [3]. Under constant load and speed, any change in the vibration signal may be attributed to the fault conditions. Nevertheless, this assumption may not be true for varying operating conditions and in most cases, the gearbox during service operates under varying or fluctuating conditions contributed by uncertain or unexpected sources [3]. Developing a robust technique for detecting gearbox deterioration when it is subjected to varying operation conditions becomes a serious issue. In addition, if the vibration signal is measured at different locations, these signals may be corrupted due to the effect from attenuation of transmission paths and interference from other sources.

Numerous analysis techniques have been fully developed and established over the years for processing vibration signals to obtain diagnostic information about progressively worsening gear faults. Earlier research on gear failure detection focused on the use of time-averaged vibration signal,

spectrum, cepstrum, amplitudes and phase modulation techniques to detect different types of gear failures. Most of these conventional approaches work well to detect abnormalities and indicate faults without providing much information about them, such as location and severity of the faults (4-5).
Condition monitoring (CM) of gearboxes plays an important role in insuring the reliability and minimum cost operations of industrial facilities [6]. CM has the capability to detect early gear faults before unexpected breakdown occurs. The main task of the designer is to guarantee the reliability of the gearbox through using high quality gear material and manufacturing technology for the gearbox design. However, the reliability and stability of the gearbox will be decreased during its operation under a harsh working environment. CM is an effective method for detecting the operating conditions of the gearbox, and gives guidance for maintenance. Machines can be monitored during operation and repaired in a convenient time and CM can further help to achieve economical operations and reduce emissions. As the fatigue gearbox test is one of the common failure tests in a gearbox, this paper explores the performance of using Time Synchronous Average (TSA) analysis and Sideband Energy Ratio (SER) to diagnose fatigue faults based on a two stage helical gearbox. Vibration and acoustic signals for different conditions including baseline case are processed by TSA and SER for feature extraction and fault diagnostics. SER has been developed specifically to auto-detect and distinguish gear defect signatures within an overall vibration signal and provide an early warning of developing gear damage. The following paper reviews the TSA technique in section 2 while section 3 details the test facility and section 4 presents and discusses the results of using TSA and SER analysis. The conclusion forms the final section.

SIGNAL ANALYSIS TECHNIQUES

Time domain techniques typically employ statistical analysis such as RMS, Kurtosis, peak value and a time synchronous signal averaging method [7]. Time domain approaches are suitable in situations where periodic vibration is observed and faults produce wideband vibration due to periodic impulses.

Time Synchronous Average (TSA)

TSA is a pre-processing technique used to isolate the vibration produced by each gear in the gearbox due to its significant suppression of random noise components. The vibration signal corresponding to one revolution of the gear of interest is sampled with the help of a tachometer and the ensemble average over the period is calculated. The synchronous averaged signal tends to eliminate the noise components that are not synchronous with the rotation of gear, leaving only the vibration signal of the gear under study during one revolution [8-9]. Therefore, detection and identification of the local defects of the gear become much simpler and effective. This technique is very applicable to investigate a gearbox composed of multiple gears since it attenuates the vibration signals from other system components. However, by simply applying this technique the early detection of gear faults is often difficult and requires more sophisticated signal processing techniques to enhance the information from the synchronous averaged signal.

Sideband Energy Ratio (SER)

In general the Sideband Energy Ratio (SER) [10] is calculated from high resolution spectrum data. Each spectrum is created from time-based waveform data generated by an accelerometer sensor and collected by the monitoring system. Several accelerometer sensors were mounted in strategic locations on the gearbox to monitor each gear mesh. The waveforms from each sensor were synchronously sampled so that the sampling frequency tracks changes in speed. This technique produces narrow spectral lines of speed-dependent frequencies, like gear mesh frequencies and associated sidebands, for variable speed machines. They are essential to accurately calculate SER. Once the spectrum is generated the SER algorithm sums the amplitudes of the first six sideband peaks on each side of the centre mesh frequency and divides by the amplitude of the centre mesh frequency.

$$\mathrm{SER} = \frac{\sum_{\mathrm{i}=1}^{6} \text{sideband amplitude } i}{\text{Centre mesh frequency amplitude}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

SER is sensitive to the sideband amplitudes relative to the centre mesh frequency. In a healthy gear mesh, any sidebands have small amplitude compared to the centre mesh frequency, or they may be missing altogether resulting in a low SER. SER is typically less than one for a healthy gear mesh. As damage develops on a gear tooth that passes through the gear mesh, the sidebands increase in amplitude.

TEST FACILITIES AND FAULT SIMULATION

The test rig shown in Fig. 1 consists of a reduction gearbox with two stages of helical gears manufactured by David Brown Radian Limited; a three phase induction motor (11kW, 1465rpm and four poles) produced by the Electro-drive Company, and a load system consisting of two flexible couplings, DC generator and resister bank. The induction motor is flanged in a cantilever type arrangement to the gearbox while the input shaft is driven by an AC motor. The motor speed and load is controlled by a variable speed drive for studying condition monitoring performance. Table 1 presents the details of the two sets of gears. The fault was fatigue tested under different operating conditions.

In the experiment, a speed signal is measured with a rotary encoder attached to the motor shaft. The vibration signal from the gear was measured using a 50 kHz sampling rate by 2 accelerometers mounted at two different locations: gearbox casing one and two in the two respective locations. To measure the sound signals an integrated BAST microphone system was used. A reference signal obtained from an optical pick-up was then utilised to synchronise the time-domain averaging of both the vibration and acoustic signals. To investigate the effect of the operating conditions (different rotating frequencies of the shaft and different loads) on the vibration and acoustic signals, the signals were recorded at 0%, 40% 60% 80% and 90% of the full load. In the following sections, we explore if fault diagnosis can be implemented effectively based on vibration and acoustic signals recorded for a gear casing at a remote location.

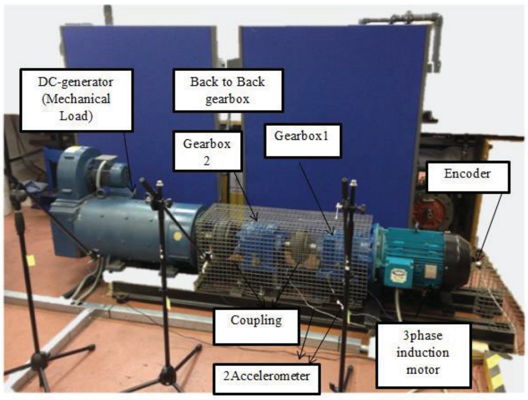

Fig1 Gearbox Test Set up

Table 1 Performance Specification of Two-Stage Helical Gearbox

Gear Parameters	1st Stage	2nd Stage
Number of teeth	58/47	13/59
Shaft speed	24.42Hz	6.64Hz
Meshing frequency	1416.36Hz	391.76Hz
Contact ratio	1.45	1.469
Transmission ratio	0.8103	4.5385

The two accelerometers connected to the gearbox can detect the vibration signal. The accelerometers have been taken from the PCB Type 336C04, attached to bases and firmly screwed in two different positions. The first was situated on the gearbox casing and the other positioned on the opposite side in the separate locations.

The acoustic signals are measured by using BAST's microphone system composed of an electrets microphone CHZ-211 and a preamplifier YG-201. The tables below show the specification for the accelerometers and microphone:

Table 2 ICP-type Accelerometer Specifications and Microphone Specification CHZ-211

Model and Serial Number	PCB Model No 338C04 accelerometer	Microphone Specification CHZ-21	Microphone CHZ-211
Frequency range	0.5Hz to 10 kHz (±5%)	Frequency response (Ref. 250Hz)	6.3Hz~20kHz (±2dB)
Sensitivity	100mV/g (± 10%)	Sensitivity	-26±1.5dB (50mV/Pa)
Temperature Range	-53 to 93°C	Temperature Range	-40°C~+80°C
Excitation Voltage	18-30 VDC	Sound field	Free sound field

A gear fatigue test was conducted by machining out a half width on input pinion. This reduction of gear loading profile increases local stress and leads to rapid and early failure. The data was collected in 1hour interval under 5different loads, and data was also collected after 20 minutes due the operation conditions. Use of Fast Fourier Transform FFT to get spectrum frequency analysis can be shown in the fig3. To investigate the effect of the operation condition (different rotating frequencies of the shaft and different loads) on the vibration signals, the signals were recorded at 0%, 40%, 60, 80 and 90% of full shaft speed and full load.

In the following sections, we would explore if fault diagnosis can be implemented effectively based on vibration and acoustic signals recorded at a remote location.

RESULTS and DISCUSSION

TSA Vibration Analysis

TSA is an effective technique in the time domain to remove noise in a repetitive signal and is widely used in vibration monitoring and fault diagnosis [11]. The SNR of a vibration signal can be improved significantly by suppressing the components which are asynchronous with those of interest. TSA is applied based on the knowledge of the revolution specifications of the rotating part. Traditionally, this requirement is met by using an external trigger signal provided by a shaft encoder, and the revolution period of rotating machinery can be obtained. Then, the vibration signal is divided into small segments according to the revolution period of the rotating part, and all the segments are summed up together so that no coherent components and asynchronous components are cancelled out. Normally, vibration signals from rotating machinery are a combination of periodic signals with random noise. Assuming a signal $x(t)$ consists of a periodic signal $x_T(t)$ and a noisy component $n(t)$, the period of$x_T(t)$ is$T0$ whose corresponding frequency is$f0$, thus the signal can be expressed [12]

$$x(t) = x_T(t) + n(t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

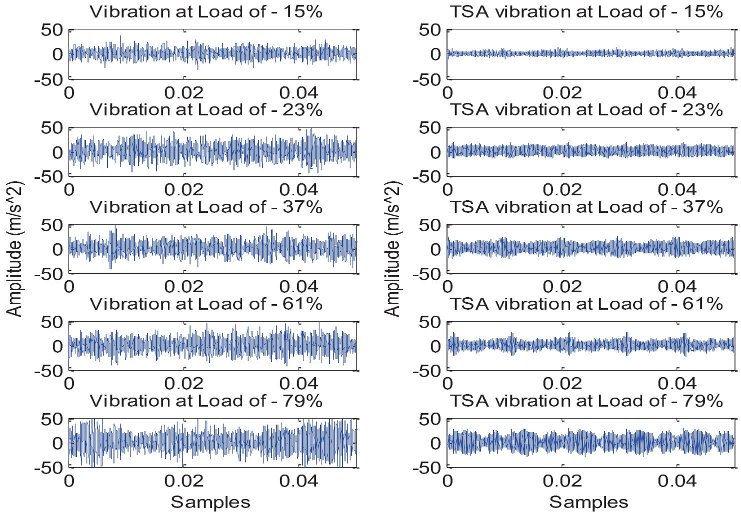

Fig 2 TSA vibration waveform from gearbox casing faulty case (Fatigue test)

Figure 2 shows the averaged vibration signal using TSA for three revolutions of the input shaft with the gearbox operating under different loads and different operating hours. The baseline is the faulty case. The findings demonstrate that the amplitude of the vibration signals increases with additional loads, and the impulse components of the vibration signals are highlighted for all the test conditions.

Vibration Spectrum Analysis

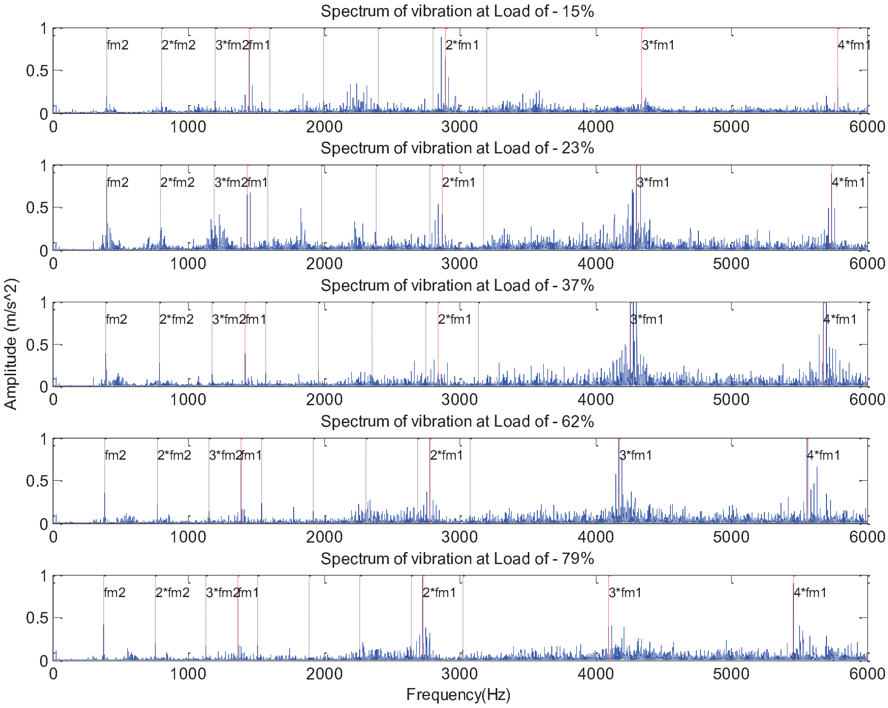

Fig3 Spectrum of vibration signal from faulty gearbox

The spectrum of the vibration signal from the faulty gearbox is shown in Fig 3. Only the frequency range from 0Hz to 6000Hz is illustrated as this range is more effective for revealing gear vibration characteristics than the higher frequency range where the more sensor resonant are induced. Further Figure 3 shows that the amplitude peaks corresponding to the first and second meshing frequency 1450 Hz and 401Hz for the first, second, third and fourth harmonics are consistently the largest feature of the spectrum, dominating the signals due to the fatigue fault, and common to the two measurement positions. Thus this feature could be used to reliably detect gear faults.

Fig 4 shows the gear relationship between amplitude and different operation hours with the faulty case (fatigue test), at full load for the frequency range 5000-5500Hz. The analysis reveals that under the faulty conditions higher amplitudes of the SER components of the gear rotational speed exist.
The amplitudes of these components are very high in the faulty case, especially for the high loads. It is believed that their appearance is caused by the fatigue tests under different conditions such as load. Therefore they can be used for the detection of such a fault. Moreover, the amplitude shows additional higher order frequency components at high frequency range. In general, the test results show that the presence of a fault in a gear is revealed by the introduction of higher amplitudes of sidebands already present, correlating with the drive shaft frequency. In addition, the fault also creates more sidebands relating to higher amplitudes of the shaft frequency.

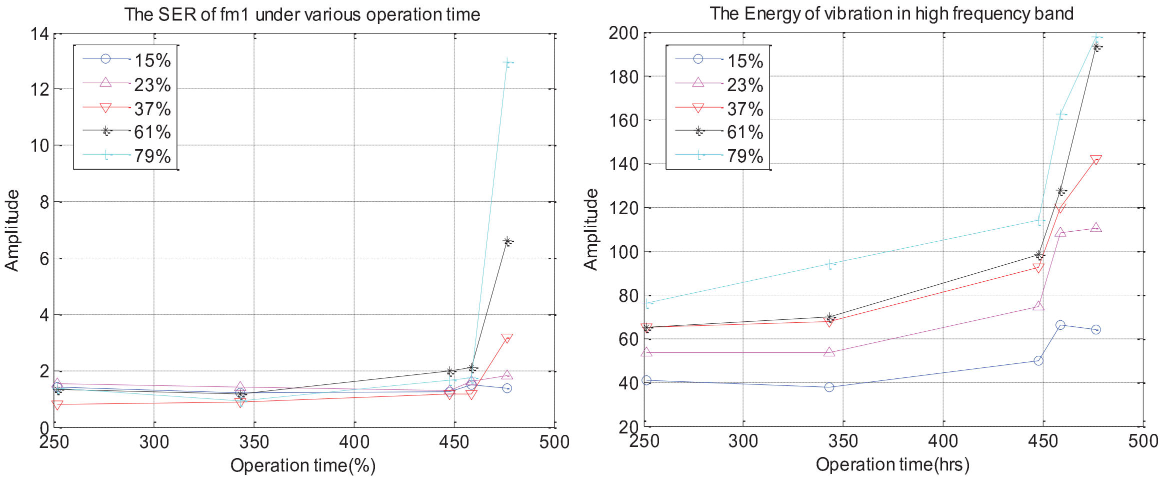

Fig4 SER of 1st meshing frequency (fm1) under various loads and energy of vibration in high frequency band

Acoustic Results (RMS and Energy of Acoustic)

Using a similar method the Root Mean Square (RMS) statistical parameter and acoustic energy have been calculated for more accurate study of the waveforms. Figure 5 shows both the RMS value of the gearbox acoustic signals for faulty gears and acoustic energy in the high frequency band under different load and operating conditions that the value patterns of the RMS and acoustic energy for the gearbox are similar for the faulty condition, mainly at small load. A slight difference in the RMS amplitude value appears as the load increases, however this difference is sufficiently significant to be considered as a fault indicator.

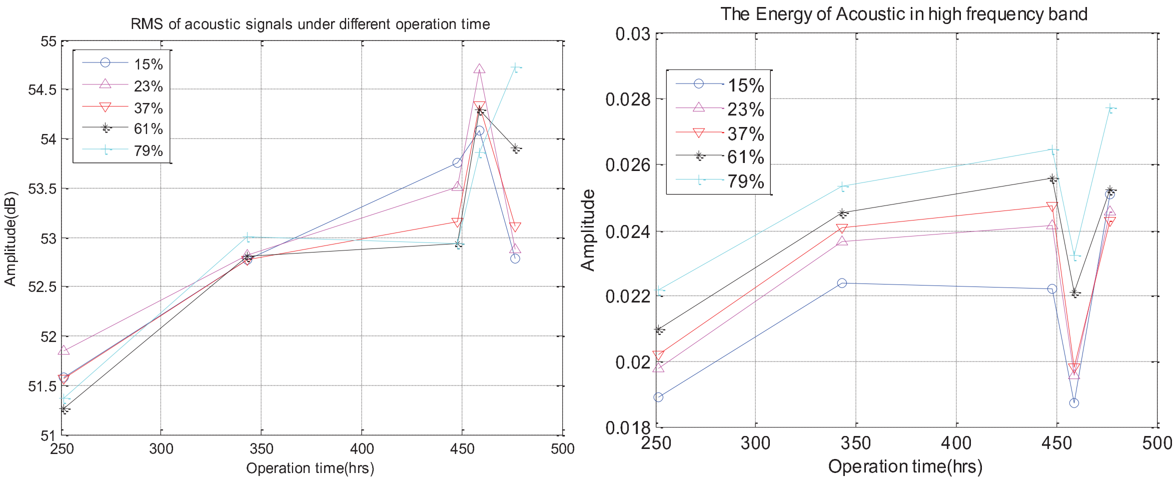

Fig 5 RMS of acoustic signals and acoustic energy in high frequency band

The findings illustrated in Figure 5 show that the average amplitude has changed at low rotational speeds. More importantly, the results appear to show an increase in the average amplitude value for most of the applied loads as fault is introduced, especially on high loads. Given these results, the average amplitude data can be used effectively to indicate gear faults in all operating conditions.

The results demonstrate that the performance of the conventional frequency domain degrades due to the fluctuation of the operating conditions. Therefore, the average amplitude signal derived from the acoustic signal may be effective for detection of fatigue faults induced in the gear system under certain specific operating conditions.

With different gear operation and the same location as seen in Figure 5, the average sideband amplitude (new feature) of the acoustic signals increase with higher load. Further these RMS values appear to increase in amplitude with the introduction of fault. The results of the special analysis described above illustrate that vibration and acoustic analysis based on TSA signals can achieve the same results from a remote position, though the amplitude of the SER is attenuated. Therefore, fault diagnosis from a remote position is certainly available with special analysis techniques.

CONCLUSIONS

Surface vibration and airborne acoustic monitoring both have distinct capabilities, advantages and disadvantages. The longstanding usefulness of conventional surface vibration consists in localised information obtainable from the rotating components, energy released by increasing friction or impacting throughout the components which allows vibration to be detectable. Similarly the energy emitted by these components is detectable by an acoustic sensor that is mounted non-intrusively. It is remote and obtains information globally from other noise sources.

The study investigated the vibration and acoustic signals measured from the gearbox and under different operating conditions and different gear life times, and which were analysed in the time domain using TSA signals and SER. The key findings indicate that the performance of traditional signal processing techniques degrades due to the fluctuation of the operating conditions. However, the new feature from the SER is effective in detecting the fatigue fault induced to the gear system under most conditions. Moreover, it can achieve the same fault detection results from a remote positioned microphone; although it's acoustic signals are distorted significantly by background-interferences. However it does not perform well under certain conditions. In future research, more advanced analysis methods should be adopted to obtain more robust features.

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