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**Original Citation**

Al-Arbi, Salem, Gu, Fengshou, Guan, Luyang, Ball, Andrew and Naid, A. (2009) Gearbox Fault Diagnosis based on Vibration Signals Measured Remotely. Key Engineering Materials, 413-41. pp. 175-180. ISSN 1013-9826

# Gearbox Fault Diagnosis based on Vibration Signals Measured Remotely

[a]Salem Al-Arbi, [b]Fengshou Gu, [c]Luyang Guan, [d]Andrew Ball, [e]A. Naid
School of Computing and Engineering, University of Huddersfield,
[a]S.Al-Arbi@hud.ac.uk, [b]f.gu@hud.ac.uk, [c]l.guan@hud.ac.uk, [d]a.ball@hud.ac.uk,
[e]a.naid@hud.ac.uk

**Keywords:** Gearbox, attenuation, interference, spectrum analysis, time synchronous averaging.

**Abstract.** In many cases, it is impractical to measure the vibrations directly at or close to their source. It is a common practice to measure the vibration at a location far from the source for condition monitoring purposes. The vibration measured in this way inevitably has high distortions from the vibrations due to the effect of the attenuation of signal paths and the interference from other sources. The suppression of the distortions is a key issue for the remote measurements based condition monitoring. In this paper, the influences of transducer locations are investigated on a typical gearbox transmission system for the detection of the faults induced to the gearbox. Several signal processing techniques' analysis results show that the attenuation and interference cause high influences on the gear transmission signals. However, time synchronous average (TSA) is very effective to detect the local faults induced to the gear system.

## 1 Introduction

Gears are used in almost all power transmission systems. For maximum availability their condition monitoring (CM) has been paid a considerable attention in recent years. This leads to that many CM techniques have been developed based on vibration signal analysis [1-2].

To obtain the gearbox vibration signal with high signal-to-noise ratio (SNR), the vibration sensors are always fixed to the gears as close as possible. However in real-world applications, it is often difficult to fix the sensor on the gearbox properly. Then, how to monitor the gear condition remotely and how to update the signal processing techniques for remote machine condition monitoring or fault diagnosis are new topics of this research field.

In this paper, the two vibration signals of gears with different faults picked up from different locations were analyzed by multiple signal processing methods to investigate the characteristics of vibration signals recorded remotely and the influence of path transmission on the performance of gear fault diagnosis.

## 2 Test Facilities and Fault Simulation

The test rig, shown in Fig. 1, consists of a reduction gearbox with two stages of helical gears. Table 1 presents the details of the two sets of gears. The faults were simulated by machining out a 20% of one tooth (fault 1), 50% of one tooth (fault 2) and 50% of two adjacent teeth (fault 3) of the pinion gear.

In the experiment, a speed signal is measured with rotary encoder attached to the motor shaft. The vibration signal from gear was measured with 50 kHz sampling rate by 2 accelerometers mounted at two different locations: gearbox casing and motor casing respectively. In the two locations, motor casing is relative far from the gear. In the following sections, we would explore if fault diagnosis can be implemented effectively based on vibration signals recorded at a remote location.

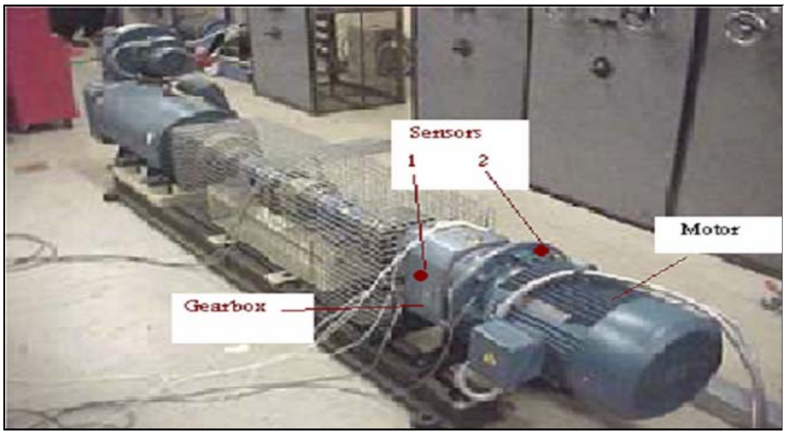


Fig. 1 Gearbox test rig

| Gear Parameters | 1st Stage | 2nd Stage |
|---|---|---|
| number of teeth | 34/70 | 29/52 |
| speed of shaft | 24.33 Hz | 6.59 Hz |
| meshing frequency | 827.73 Hz | 342.73 Hz |
| contact ratio | 1.359 | 1.479 |
| overlap ratio | 2.89 | 1.478 |

Table 1 Gearbox speccification

## 3 Signal Analysis Techniques

### 3.1 Time Synchronous Average

TSA is a pre-processing technique used to remove non-stationary noise from periodical signal. The fundamental principle behind this method is that vibration signal of the gear can be regarded as cyclostationary. The synchronous averaged signal tends to cancel out the vibration components that are not synchronous with the rotation of gear, leaving only the vibration of the gear in one revolution. Therefore, local variations in the vibration signal become more visible [3].

This technique is useful to investigate a gearbox composed of multiple gears since it attenuates the vibration from other system elements. More sophisticated signal processing techniques can be used based on the synchronous averaged signal to achieve more robust performance. However, TSA method requires relatively large amount of data and limited speed fluctuation to guarantee the convergence of ensemble averages.

### 3.2 Time Domain Statistical Parameters

Time-domain approaches are suitable in situations where periodic vibration occurs and faults produce periodic impulses as a wide bands noise [4]. Several statistical parameters of time-domain signal are applicable for mechanical fault detection [5], such as root mean square (RMS), kurtosis and crest factor (CF).

These parameters characterize the time-domain vibration signal statistically to indicate only some aspects of the machine status respectively. Thus, the statistical information behind the time-domain vibration signal should be considered and processed collaboratively. Single statistical parameter can not be a reliable indicator of machine conditions.

### 3.3 Frequency Domain Methods

Frequency domain methods are a class of the most common methods used for analyzing mechanical vibration signals. Defects such as local damage are expected to be identified by this method as an increase of modulation sidebands in spectrum. These sidebands are located on both sides of gear meshing frequency and its harmonics and are separated by integer multiples of gear rotation frequency.

In the following sections, spectral analysis of the original and TSA vibration signals from different locations would be calculated and compared.

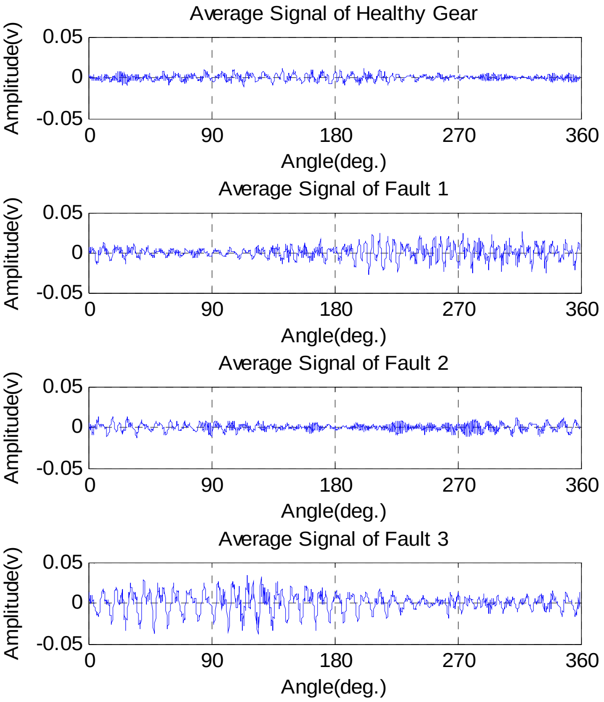
## 4 Comparison of Fault Diagnosis

In gear transmission system, a local fault causes impacts and the impulses of this transient event may be detected as instantaneous pulse of the vibration signals in each revolution. Fault diagnosis is just based on the extraction of this pulse noise. In this section, multiple signal analysis methods were employed to compare the effect and possible problems of remote fault diagnosis.

### 4.1 Time-domain TSA Analysis

The time synchronous averaged vibration signal for a healthy gear and three faulty cases (fault1, fault2 and fault3) at two locations are shown in Fig. 2 and Fig. 3 respectively. There are clear differences between the waveforms with different gear conditions. In both figures, the pattern of TSA vibration signal changes with the severity of the faults.

However, for an identical fault, different patterns are shown in the two figures, especially in the case of fault 3. This illustrates that remote measurement of the gear vibrations is interfered by the path transmission or other noise source, such as the motor’s vibration. Obviously, this interference is limited; distinguishing differences are shown among the TSA patterns of different gear casings.



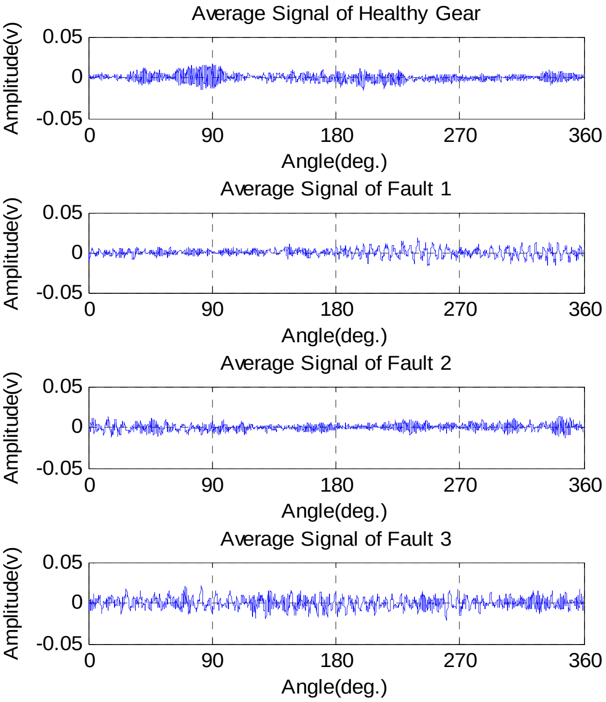


Fig. 1 TSA vibration waveform from gearbox casing for healthy and faulty cases

Fig. 2 TSA vibration waveform from motor casing for healthy and faulty cases

### 4.2 RMS Values, Kurtosis and Crest Factor

Table 2 shows the average values of RMS, kurtosis and crest factor of the vibration signal for healthy and faulty gears without and with applying TSA. The results reveal significant change between the RMS values with and without TSA confirms that the attenuation and interference of vibration signals may significantly alter the overall RMS values.

This table also reveals crest factor is not sensitive to the faults of the gear and significant variation of the kurtosis values of the different measurements possibly shows different gear faults. However, no consistent pattern emerged. For example, in the fault 3 case, kurtosis of the signal from gearbox casing without TSA was higher than for other gear conditions, whereas in the fault 2 cases kurtosis with TSA for the same transducer positioned was a minimum.

Though these three statistical parameters, especially crest factor, are not effective to indicate the gear faults, but the analysis results of vibration signal from gearbox casing and motor casing changes as almost the same trend for the different gears. Therefore, remote condition monitoring is available if appropriate features can be extracted.

| Sensor location | Gear condition | RMS |  | Kurtosis |  | Crest Factor |  |
|---|---|---|---|---|---|---|---|
|  |  | Raw | TSA | Raw | TSA | Raw | TSA |
| Gearbox Casing | Healthy | 0.0464 | 0.0035 | 0.2116 | 0.1930 | 5.3913 | 3.4197 |
|  | Fault 1 | 0.0517 | 0.0078 | 0.1948 | 0.7495 | 5.1862 | 3.6408 |
|  | Fault 2 | 0.0486 | 0.0041 | 0.2205 | 0.1272 | 5.2060 | 3.3529 |
|  | Fault 3 | 0.0661 | 0.0112 | 0.3608 | 0.4790 | 5.5371 | 3.3993 |
| Motor Casing | Healthy | 0.0701 | 0.0043 | 0.2235 | 0.9028 | 5.0764 | 3.8358 |
|  | Fault 1 | 0.0566 | 0.0046 | 0.1291 | 0.8930 | 5.0139 | 3.8798 |
|  | Fault 2 | 0.0654 | 0.0039 | 0.1022 | 0.3185 | 4.9831 | 3.6484 |
|  | Fault 3 | 0.0932 | 0.0064 | 0.2454 | 0.0633 | 5.2114 | 3.3458 |

Table 2  Common Statistical Parameters

### 4.3 Frequency Domain Analysis

The vibration from normal and faulty gears contains the fundamentals and harmonics of the meshing frequency. Any change in the spectrum, such as variations in the amplitude of the meshing frequencies and their harmonics, can be attributed directly to the fault condition of the gears [6].

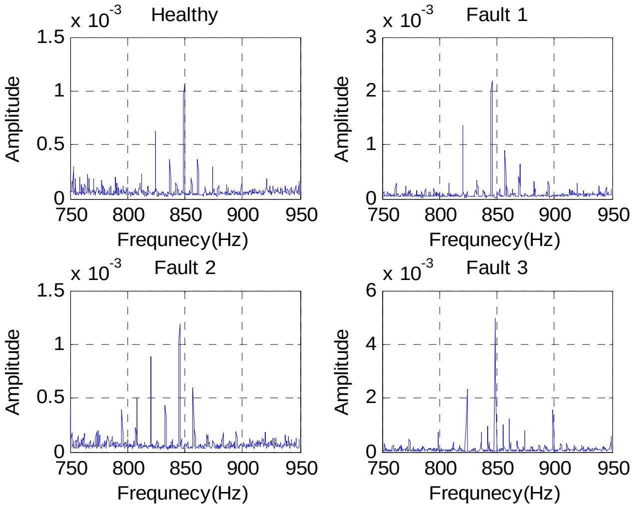


Fig. 4 Averaged spectrum of signals from gearbox casing for healthy and faulty cases

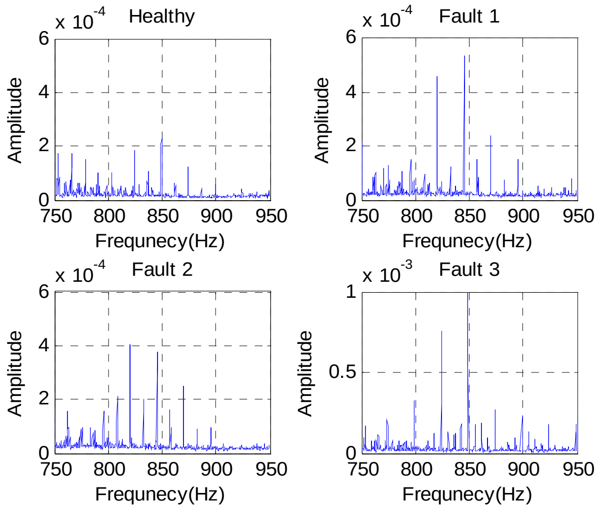


Fig. 5 Averaged spectrum of signals from motor casing for healthy and faulty cases

The averaged spectrums of the healthy and faulty gears' vibration signals recorded from two locations are shown in Fig. 4 and 5. From the two figures, it can be seen there are clear discrete components in the low frequency range.

From Fig. 4, 5 and Table 3, the spectrum of the vibration signals shows the amplitude peak value corresponding to the first stage meshing frequency is consistently the largest value of the spectrum. There appears an increase in the amplitude with the introduction of faults at two locations. Amplitudes of the signals at the motor casing are lower then on the gearbox casing due to the effect of transmission paths on the vibration signal.

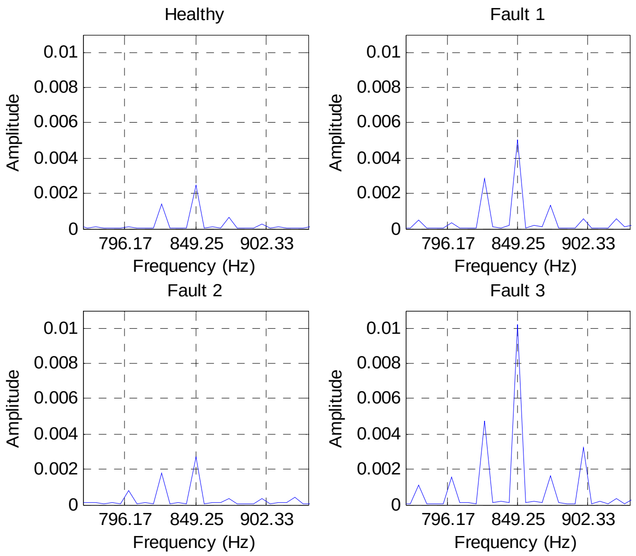


Fig. 6 Spectrum of TSA signals from gearbox casing for healthy and faulty cases

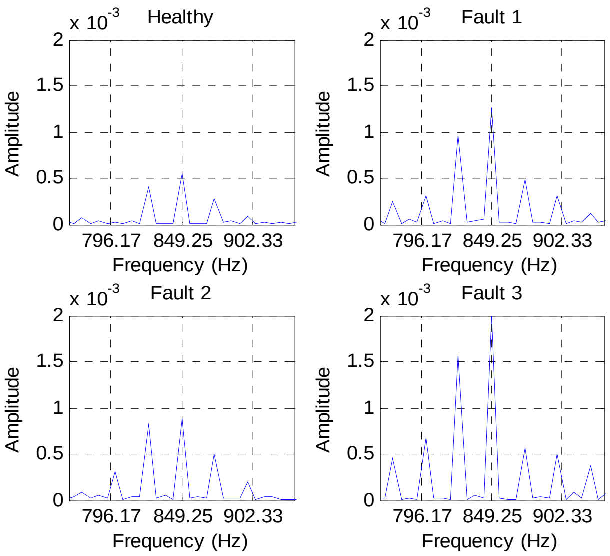


Fig. 7 Spectrum of TSA signals from motor casing for healthy and faulty cases

| Sensor location | Gear Condition | Amplitude(x$10^{-5}$) of $fm_1$ | |
|---|---|---|---|
| | | FFT | TSA |
| Gearbox Casing | Healthy | 106.1 | 245.7 |
| | Fault 1 | 215 | 501.7 |
| | Fault 2 | 118 | 269.2 |
| | Fault 3 | 502.1 | 1021.0 |
| Motor Casing | Healthy | 26.9 | 54.86 |
| | Fault 1 | 52.97 | 125.7 |
| | Fault 2 | 38.29 | 87.41 |
| | Fault 3 | 99.4 | 204.6 |

Table 3 Amplitide of the first meshing frequency

| Sensor location | Gear Condition | Amplitude (x $10^{-5}$) $fm_1 \pm fr_1$ | | | Amplitude (x $10^{-5}$) $fm_1 \pm 2\ fr_1$ | | |
|---|---|---|---|---|---|---|---|
| | | FFT | TSA | | FFT | TSA | |
| | | | $fm_1$-$fr_1$ | $fm_1$+$fr_1$ | | $fm_1$-2 $fr_1$ | $fm_1$+2 $fr_1$ |
| Gearbox Casing | Healthy | 28.39 | 139.6 | 65.37 | 15.48 | 14.58 | 28.96 |
| | Fault 1 | 63.96 | 218.6 | 132.9 | 31.48 | 36.54 | 58.03 |
| | Fault 2 | 15.91 | 180.7 | 36.9 | 18.35 | 76.42 | 35.51 |
| | Fault 3 | 81.46 | 477.6 | 166.7 | 153.3 | 158.3 | 325.3 |
| Motor Casing | Healthy | 12.07 | 40.44 | 27.91 | 61.65 | 1.178 | 7.963 |
| | Fault 1 | 24.00 | 95.89 | 47.65 | 15.33 | 30.63 | 31.24 |
| | Fault 2 | 25.19 | 81.77 | 49.53 | 9.8 | 31.15 | 20.02 |
| | Fault 3 | 27.41 | 156.7 | 56.06 | 23.42 | 67.51 | 50.58 |

Table 4 Amplitude of $fr_1$.sidebands

The spectrum of TSA signals are shown in Fig. 6 and 7. Table 3 depicts the spectral values corresponding to the first stage meshing frequency with the four gears at different locations. It can be seen that the spectral amplitudes at meshing frequency and its sidebands increase with the severity of the faults. More importantly, the results from motor casing show the difference between faults as clear as that from the gearbox casing.

Table 4 shows the spectral peak values at the harmonics of the meshing frequency modulated by shaft frequency. After TSA, the faults of the gears can be distinguished more obviously according to these spectral peak values at the special frequencies.

The special analysis results described above illustrate that spectral analysis based on TSA signals can achieve the same results at a remote position, though the amplitude of the spectrum is attenuated. Therefore, fault diagnosis from remote position is certainly available with some special spectral analysis techniques.

## 5 Conclusions

In this research, the vibration signals measured from different locations were analyzed in both the time domain and the frequency domain. The results show conventional spectral analysis technique is not sensitive to the remote location of the sensor and the noise and attenuation introduced by path transmission. Spectral analysis based on TSA signals is a more appropriate solution to the remote fault diagnosis problem. It is difficult for time-domain parameters to indicate the status of the gear explicitly. Although they changes with the faults of the gears, no consistent pattern can be extracted from these parameters. This paper shows that remote fault diagnosis is possible in both theory and practical application. To develop more effective and robust diagnosis features from remote measurements with more advanced data analysis is the future work of this subject.

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