# REMOTELY GEAR CONDITION MONITORING USING TRADITIONAL SIGNAL PROCESSING TECHNIQUES

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## ABSTRACT

*For gearbox condition monitoring, because the difficulty of sensor installation, it is a common practice to measure the vibration at a location far from the fault source. In addition operating the gearbox under different loads and speeds also produces the vibration signals with different components. The vibration measured in this way may be distorted significantly by the effect of signal transmission paths and the interference from other sources. The suppression of distortions is thus a key issue for the remote measurements based condition monitoring. In this paper, the influences of transducer locations and operating conditions on the vibration signal are investigated on a typical gearbox transmission system for the detection of the faults induced to the gearbox. The experimental study results show that the performance of traditional signal processing techniques is not sufficient to reveal fault detection information. However, the new feature from the spectrum of time synchronous average (TSA) signal is very effective in suppressing noise and hence leads to better detection of the local faults induced to the gear system.*
**Keywords** gearbox, attenuation, interference, traditional analysis

## INTRODUCTION

Gears are the most universally used machine elements in all power transmission systems. With higher requirements in operating speed and applied load, there is a general increase in premature failures in gear components due to excessive wear and material fatigue, such premature failures often result in substantial financial losses, and sometimes may even lead to catastrophic consequences. Until now, a large amount of research in the field of condition monitoring of a gearbox has been conducted using several techniques based on vibration signal analysis [1-2]. 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 operation conditions and in most cases, the gearbox operates under varying or fluctuating conditions contributed by uncertain or unexpected sources, during service [3]. Developing a robust technique for detecting gearbox deterioration turns out to be a serious issue, when it is subjected to varying operation conditions. In addition, if the vibration signal is measured at different locations, these signals may be corrupted due to effect of attenuation of transmission paths and the interference from other sources.

In this work, two vibration signals of gears with two different faults were picked up from different locations with different operation conditions. These signals were analyzed by multiple signal processing methods. This paper targeted to investigate the characteristics of vibration signals obtained from different locations under different operation conditions so that an effective feature can be developed to detect and diagnose the gear fault severity.

## 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 introduced by machining out a 50% of one tooth (fault 1), and one complete tooth (fault 2) of the pinion gear to simulate broken tooth occurring commonly in practice.

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 target gear set to be monitored.

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 50%, 75% and 100% of full shaft speed and 40%, 60% and 80% of the full load.

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

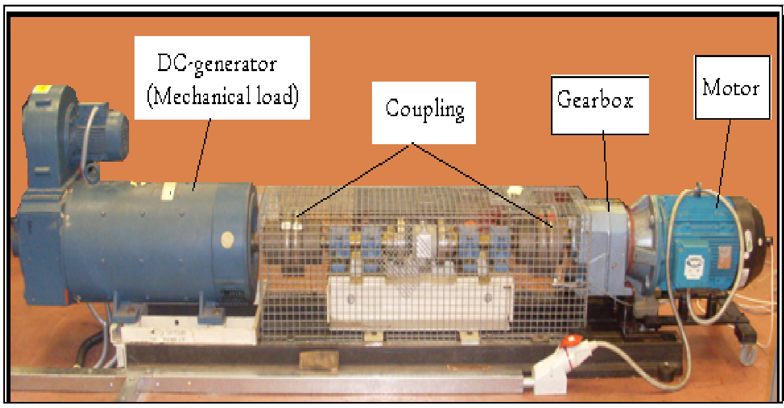


Fig. 1 Gearbox test rig

| 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 specification

## SIGNAL ANALYSIS TECHNIQUES

Time domain techniques typically employ statistical analysis such as RMS, Kurtosis, Crest factor and a time synchronous signal averaging method [4]. Time domain approaches are suitable in situations where periodic vibration is observed and faults produce wideband vibration due to periodic impulses [5-6].

### 3.1 Time Synchronous Average

TSA is a pre-processing technique used to isolate the vibration produced by each gear in the gearbox because of 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 completed. 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 revaluation [5, 7]. 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, the very early detection of the gear faults is often difficult by simply applying this technique and requires more sophisticated signal processing techniques to enhance the information from the synchronous averaged signal.

### 3.2 Time Domain Statistical Parameters

Traditional statistical parameters such as RMS, kurtosis, and crest factor characterize the time-domain vibration signal statistically to produce an overall indication of some aspects of the machine status respectively. Because of their easy understanding and wide awareness in engineering, they are still used commonly for fault or abnormality indication. However, individual statistical parameter cannot be a reliable indicator of machine conditions. The statistical information behind the time-domain vibration signal should be considered and processed collaboratively.

### 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 sidebands around mesh frequency in spectrum. These sidebands are separated by integer multiples of gear rotation frequency which are originated because of the growing fluctuation of shaft rotary due to local gear fault.

A new feature from the spectrum of TSA signal is extracted to characterize the change of the amplitudes of the characteristic frequencies. It is defined as the average amplitude of the sidebands around the meshing frequency. These sidebands are the harmonics of the shaft frequency (fr) modulated by the meshing frequency (fm). For gearbox casing location, the selected sidebands are fm±1*fr, fm±2*fr, fm±3*fr and fm±4*fr; for motor casing location, the selected sidebands are fm±1*fr and fm±4*fr.

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

## COMPARISON OF FAULT DIAGNOSIS

In gear transmission system, a local gear fault such as broken tooth causes impacts between mesh teeth and result in 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 Synchronous Average

Time synchronous average (TSA) is an effective method in application of machinery fault diagnosis. It removes the interference of random noise from the vibration single. In this paper, TSA is applied to raw vibration signals as a signal pre-processing technique to eliminate the random noise and improve signal-noise ratio of the signal to achieve robust performance.

## 4.2 RMS Values, Kurtosis and Crest Factor

Figures 2-4 shows the average values of RMS, kurtosis and crest factor of the vibration signal for healthy and faulty gears with applying TSA under different operating conditions. These three statistical parameters vary with the severity of the gear faults and sensor locations. However, no consistent pattern can be observed. Then these features cannot indicate the faults effectively. Advanced signal processing techniques should be adopted to obtain a robust feature for gearbox fault diagnosis.

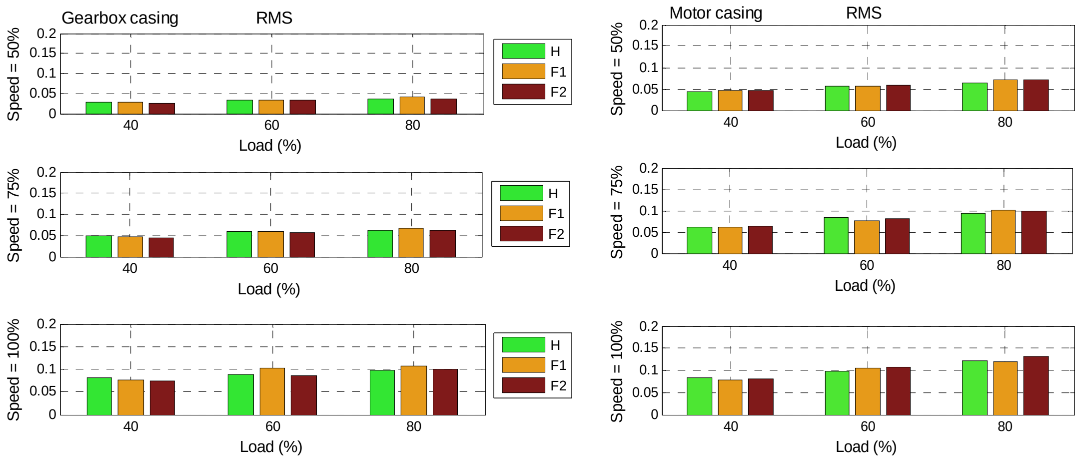


Fig .2 Average values of RMS of the vibration signal for healthy and faulty gears

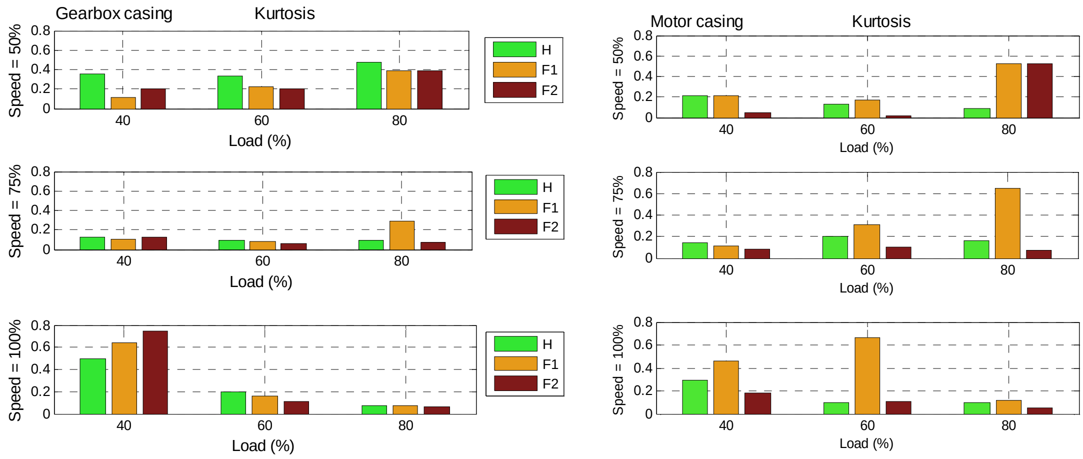


Fig. 3 Average values of Kurtosis of the vibration signal for healthy and faulty gears

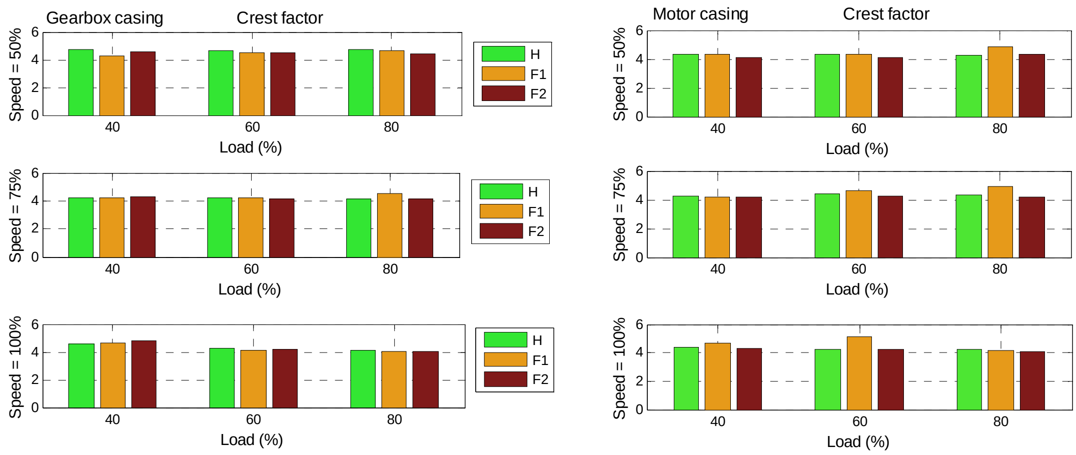


Fig. 4 Average values of Crest factor of the vibration signal for healthy and faulty gears

### 4.3 Frequency Domain Analysis

Any change in the spectrum of the vibration signal, such as fluctuations in the amplitude of the sidebands of the meshing frequency and its harmonics, can be attributed directly to the fault condition of the gears [6]. The averaged spectrums of the healthy and faulty gears with the same and different operation condition' vibration signals recorded from two locations are shown in Figs. 5-8. These figures depict the peak values of the first stage meshing frequency and sidebands for the two locations and different operation condition. It can be seen that the spectral amplitudes at mesh frequency and its sidebands changes with the gear operation condition and severity of the faults.

In Fig. 5 and 6, where the gearbox was operated by the same parameters, these peaks appear increase in the amplitude with the introduction of faults at two 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. Amplitudes of the signals at the motor casing are lower than on the gearbox casing due to the effect of transmission paths on the vibration signal.

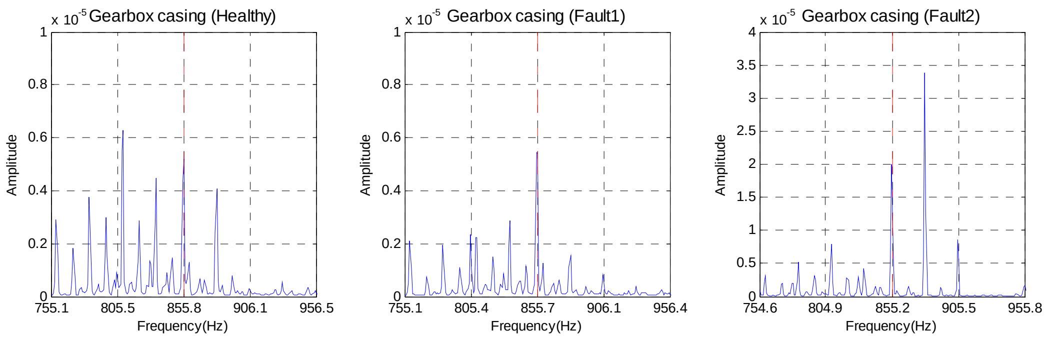


Fig. 5 Averaged spectrum of signals from gearbox casing for healthy and faulty cases under 40% load and full speed

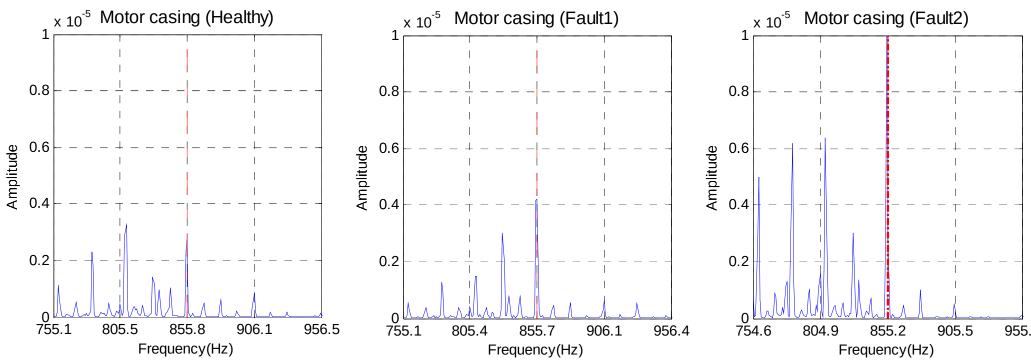


Fig. 6 Averaged spectrum of signals from motor casing for healthy and faulty cases under 40% load and full speed

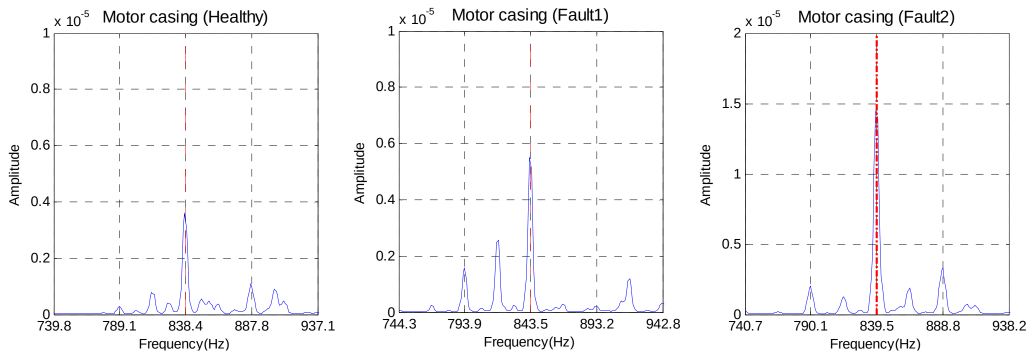


Fig. 7 Averaged spectrum of signals from motor casing for healthy and faulty cases under 80% load and full speed

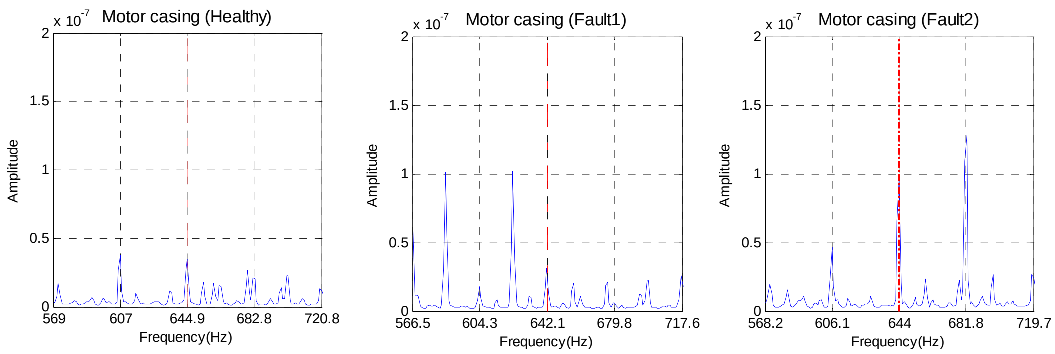


Fig. 8 Averaged spectrum of signals from motor casing for healthy and faulty cases under 80% load and 75% speed

With different gear operation and same location as seen in Fig 6,7 and 8 the spectrum of the vibration signals shows that the average amplitude peak values increase with increasing load at the same location, also these peaks appear an increase in the amplitude with the introduction of faults at two locations.

Theorically, the sidebands of the meshing frequency are due to the meshing frequency modulated by the shaft frequency *($f_r$)*. The amplitudes of the sidebands increase with the fault of the gear as shown in Fig 5 and Fig 6. Then a new feature can be defined as the average amplitude of the sidebands around the meshing frequency *($f_m$)* in TSA signal spectrum to characterize of the healthy condition of the gears.

| **Operation Parameters** | | **Sensor Location** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Gearbox Casing** | | | **Motor Casing** | | |
| | | **New Feature (x $10^{-6}$)** | | | **New Feature (x $10^{-6}$)** | | |
| Load | Speed | H | F1 | F2 | H | F1 | F2 |
| 40 | 50 | 0.019 | 0.050 | 0.051 | 0.017 | 0.036 | 0.085 |
| | 75 | 0.117 | 0.202 | 0.272 | 0.041 | 0.076 | 0.454 |
| | 100 | 0.911 | 0.779 | 6.449 | 0.510 | 0.908 | 1.220 |
| 60 | 50 | 0.067 | 0.139 | 0.451 | 0.013 | 0.048 | 0.074 |
| | 75 | 0.034 | 0.158 | 0.377 | 0.026 | 0.039 | 0.086 |
| | 100 | 2.180 | 2.828 | 3.559 | 0.655 | 0.748 | 1.043 |
| 80 | 50 | 0.042 | 0.111 | 0.532 | 0.006 | 0.028 | 0.030 |
| | 75 | 0.029 | 0.283 | 0.405 | 0.009 | 0.057 | 0.011 |
| | 100 | 0.461 | 1.428 | 1.273 | 0.320 | 0.848 | 0.989 |

Table 2. Average amplitudes of mesh frequency and sidebands

Table 2 depicts the values of the feature with the three gears status at different locations. It can be seen that this feature 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.

With different gear operation and same location as seen in Figs 9-10, the average sideband amplitude (new feature) of the vibration signals increase with higher load at the same location, also these peaks values appear an increase in the amplitude with the introduction of faults at two locations.

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.

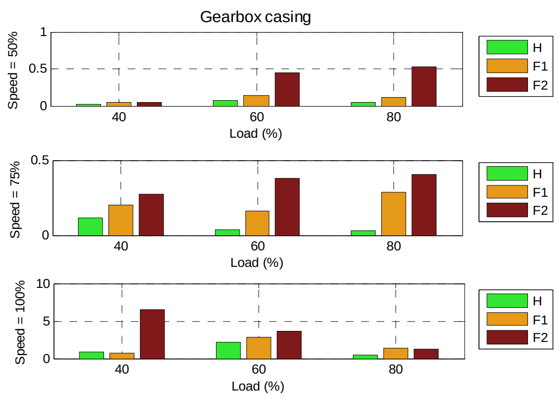


Fig. 9 Average amplitudes of sidebands on the gearbox casing

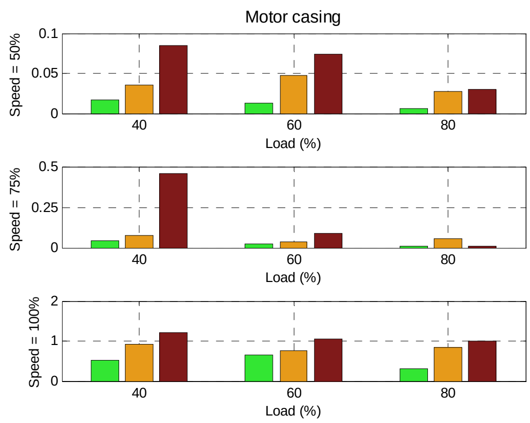


Fig. 10 Average amplitudes of sidebands on the motor casing

## CONCLUSIONS

In this research, the vibration signals measured from different locations and different operating conditions were analyzed in both the time domain and the frequency domain of the TSA signals. The results show that the performance of traditional signal processing techniques degrades due to the fluctuation of the operating conditions. However, the new feature from the spectrum of TSA signal is very effective to detect the local faults induced to the gear system under most conditions. Moreover, it can achieve the same fault detection results at a remote position, although the vibration is distorted significantly by transmission paths and interferences. But it does not perform well under some special conditions as shown in Table-2. In the future works, more advanced time-frequency analysis methods should be adopted to obtain more robust features.

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