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Vibration-Based Fault Diagnosis of Spur Gear Operating Under Constant Speed Using Time Synchronous Averaging Method

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ABSTRACT
This paper presents a vibration-based fault diagnosis method for spur gear operating under constant speed. Vibration is the most usable signal obtained from any rotary machine, just using a simple accelerometer. As gear is one of the machines' most critical components, it is crucial to identify the problem early in damage propagation. But it is quite difficult to distinguish between a healthy signal and a faulty signal at an early stage in the time domain and even in the frequency domain. Time Synchronous Averaging Method (TSAM) can be the right solution for this problem. In this paper, a simulation-based approach has been proposed to gear fault identification purposes using the MATLAB platform. Alongside TSAM, a quantitative comparison of both healthy and faulty gear's statistical features has been presented in this paper. Due to rapid industrial growth, the early fault detection and reduction of production downtime have become a prime concern for maintenance engineers. The proposed method can be handy for them.

Keywords: Vibration, fault diagnosis, condition monitoring, predictive maintenance, rotary machine elements.

1. Introduction

Over the last few years, fault diagnosis of rotary machine elements, especially gear, bearing, etc., has become a topic of interest for researchers. This is due to the change of industry outlook towards machine maintenance. Generally, three standard maintenance practices are available in our industries [1]. They are reactive maintenance, preventive maintenance, and predictive or condition-based maintenance. Reactive maintenance means no maintenance. When any failure occurs, the faulty parts are entirely replaced by a new one. This type of maintenance is also known as breakdown maintenance. Preventive maintenance is calendar-based maintenance. It is done regularly based on the OEM (Original Equipment Manufacturer) recommendation. On the other hand, predictive maintenance is the most popular maintenance strategy adopted by the maintenance people, where maintenance is done based on statistical analysis. There was a time when maintenance was considered a cost centered item. Due to the rapid development of predictive maintenance technology, the cost centered object has been transformed into a profit-centered one. Besides this, the immense growth of artificial intelligence and machine learning have made fault diagnosis more exciting topics. Researches are not only limited to diagnosis only. They are gradually moving towards machine prognosis.

Previously researchers have developed lots of methods for gear fault diagnosis. *Lin and Qu* [2] proposed a denoising method based on Morlet CWT in 2000 to extract periodic impulses features of gearbox immersed in the noise. But this method only suitable for noise reduction, not for fault detection. *Wang et al.* [3] proposed the gear fault diagnosis method based on the autoregressive model in 2002. It applies a signal averaging technique to distinguish between healthy gear and faulty gear. In 2007 *D. Yu at al.* [4] used a time-frequency entropy method to diagnose gear fault. This method can identify the fault but unable to explore the fault pattern of the gear. The next year 2008, *J. Cheng at al*. [5] proposed a method based on empirical mode decomposition that applies frequency family separation techniques to identify gear fault. A hybrid intelligent gear faulty diagnosis method has been developed by *Y. Lei et al*. [6] in 2010 for gear fault diagnosis. This method can automatically detect various faults of different categories efficiently. In 2012, Z. Shen et al. [7] proposed a novel gear fault diagnosis method that applied Empirical mode decomposition and multi-class Transductive support vector machine (TSVM) combine to identify gear fault up to 91.62%. Still, a significant percentage of faulty prediction is indicated by this paper. In 2015 D. Yang et al. [7] presented a paper applying Support Vector Machine (SVM) optimized by an artificial bee colony algorithm for gear fault diagnosis. It was good research for finding the optimum parameter of fault diagnosis.

The rest of the paper has been organized as follows. Section **2.** describes the methodology. In section **3.** Results and Discussions Portion has been introduced. The article has been concluded in section **4.**

2. Methodology

The proposed method is a simulation-based approach to diagnose gear fault using TSAM and various statistical parameters like RMS, Kurtosis, Skewness, etc. The simulated vibration data collected from the gear and pinion system is used to analyze the system's healthy and faulty characteristics. Some of the boundary condition that was considered during this simulation is given in Table 1. Initially, a healthy pair of gear and pinion was considered.

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Table 1 Boundary Conditions.

Condition Parameter	Data
Gear Teeth no *Tg*	30
Pinion Teeth no *Tp*	20
Sampling Frequency *fs*	20000 Hz
Driving speed (pinion) *Np*	1500rpm
Pinion frequency *fp*	25Hz

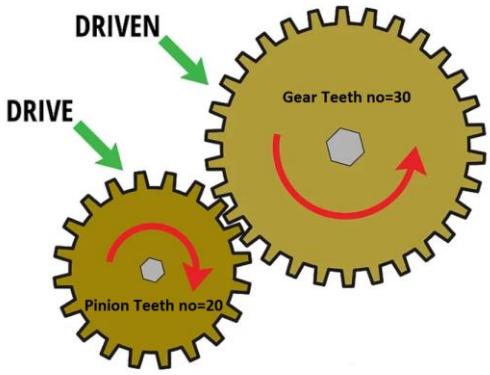

Fig.1 Gear-Pinion Combination at Healthy State.

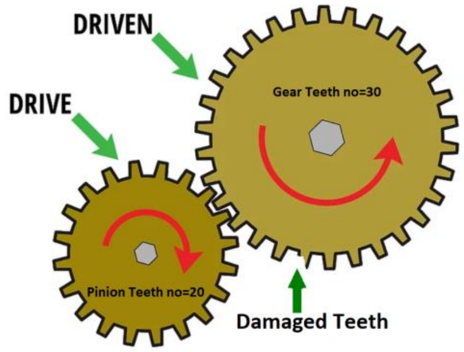

Fig.2 Gear-Pinion Combination at Faulty State.

The pinion is given the driving speed of 1500rpm. The frequency of driven gear can be calculated using the following formula.

$$f_g = f_p * \frac{T_p}{T_g} \quad (1)$$

Where,

f_g = Gear Frequency

T_p = Number of teeth of Pinion

T_g = Number of teeth of the gear

The Gear Mesh frequency can be calculated by

$$f_{mesh} = f_p * T_p \quad (2)$$

After the generation of simulated vibration data for a healthy gearbox system, high-frequency impacts is applied to the signal. It may be due to a faulty gear tooth, as shown in Fig. 2.

Table 2 Statistical Time Domain Features [8]

Statistical Parameter	Equation
RMS	$x_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^{\,2}}$
Variance	$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2$
Kurtosis	$x_{kur} = \frac{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^4}{(N-1)\sigma^4}$
Skewness	$x_{ske} = \frac{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^3}{(N-1)\sigma^3}$

To make the data more realistic, some additional noise signal was added with both healthy and faulty signals.
Using Table 2, statistical parameters for both healthy and faulty gear have has been calculated. It makes quantitative comparison of various time-domain features. Using this feature, health indicators of the system can be constructed.

2.1 Time Synchronous Averaging Method (TSAM)

Time synchronous averaging (TSA) is a signal processing technique used to extract periodic waveforms from noisy data [10-11]. TSAM is a useful technique for gearbox analysis. Since it allows the vibration signature of the examined equipment to be isolated in the gearbox from other gear and noise sources not synchronous with that unit, it is possible to adjust shaft speed variations and disperse spectral energies a neighboring gear mesh bin.
TSA of vibration signal can be calculated using the following equations.

$$An = \frac{An-1 \ *(n-1) + Tn}{n} \quad (3)$$

Where Tn = n[th] frame of the time block signal
An = n[th] average of the time block signal
N = average number given
n=1, 2, 3……….N

$$A_N = \frac{A_1 + A_2 + A_3 + \cdots A_{N-1}}{N} \quad (4)$$

3. Results and Discussions

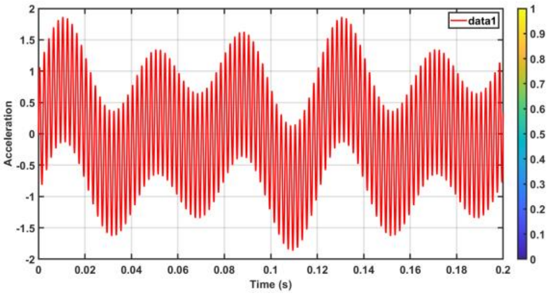

Fig.3 Time Vs. Acceleration curve at Healthy State.

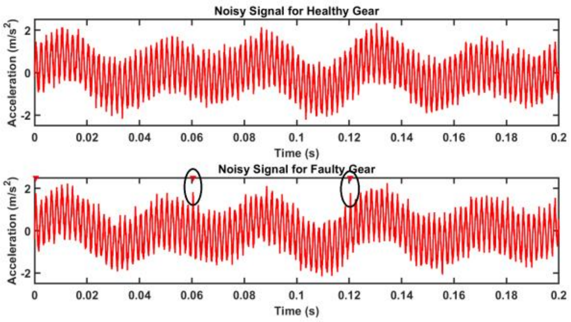

Fig.4 Time Vs. Acceleration curve at heathy and faulty state with noise.

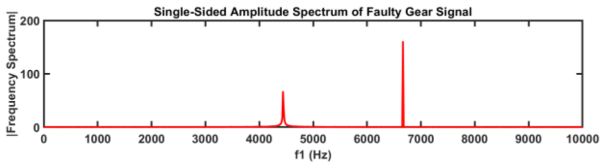

Fig.5 Frequency spectrum of faulty gear signal.

Noise-free vibration signal generally becomes sinusoidal in nature. Based on this assumption, the vibration signal is generated at the gear-pinion meshing point through the accelerometer. By intentional creation of one tooth broken at driven gear as shown in Fig.2 faulty signal was generated.

Fig.3 is showing the time series data for the accelerometer. In this signal, all the sources have been considered. The signal consists of pinion waveform, gear waveform, and gear-pinion meshing waveform. It has been added.

As realistic signals are always surrounded by noise, some White Gaussian noise signals were added to both healthy and faulty gear signals. It is noticed from Fig.4 that there is a minor variation in the time-domain signal that is quite difficult to detect.

Applying Fast Fourier Transform to the faulty gear signal has noticed a clear spike, as shown in Fig.5.

Plotting the power spectrum shows the aspirated peaks at *fg*, *fp*, and f_{Mesh}. Although, the noise in the signal does not differentiate the sideband peaks at the sideband. Making a little bit of zoom creates a precise scenario, as shown in Fig.7. But it isn't easy to differentiate between peaks for sideband and gear frequency. It becomes problematic if the pinion also becomes faulty. Fig.8 is for the Visualization of the TSA for only rotation. The effect is relatively easier to observe on the TSA sign for the gear, whereas it is averaged out for the pinion shaft. The effect's position, indicated on the graph with a pointer, has a greater amplitude than adjacent gear-mesh crests.

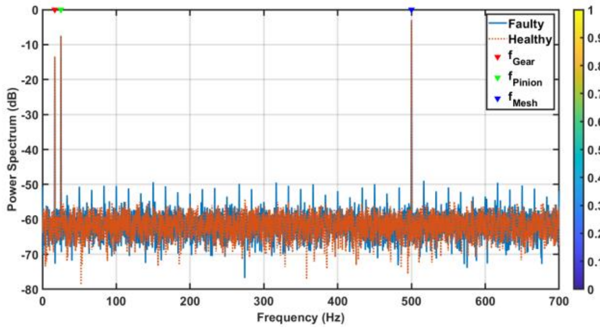

Fig.6 Power Spectrum of Faulty Gear Signal.

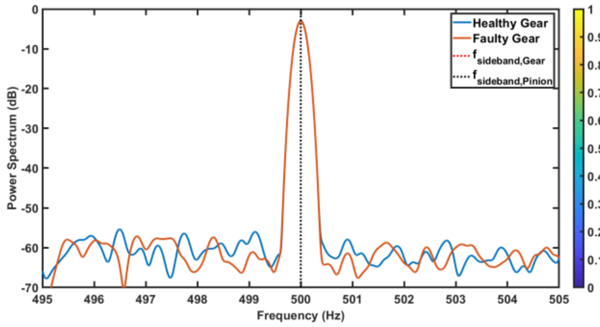

Fig.7 Zoom in Mode of Power Spectrum of Faulty Gear Signal.

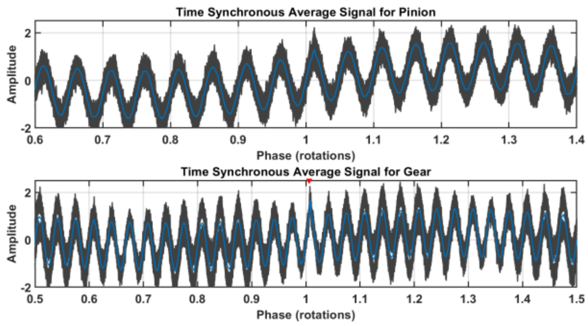

Fig.8 Time Synchronous Signal for both gear and pinion.

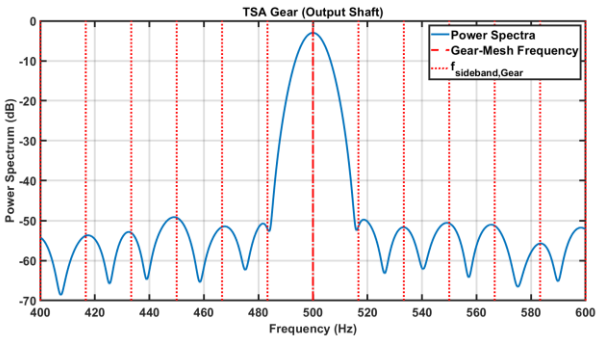

Fig.9 Power Spectrum of TSA signal (Gear).

Applying Time Synchronous Averaging Method solves this problem. TSAM finds out zero-mean random noise by averaging the signal and any frequency not involved with the undermine shaft frequencies.

Plotting TSA for both gear and pinion as shown in Fig.9 it can be noticed that a prominent peak at the locations of sideband on the spectrum of the TSA gear signal is available there. But no sideband peaks are open for pinon. It indicates pinion is potentially in healthy condition, and some faults have occurred in the gear section.

Calculating the statistical parameter in the time domain features some noticeable difference also found from this simulated data.

Table 3 Quantitative comparison of the statistical parameters of both healthy and faulty gear.

SN	**Statistical Parameter**	**Healthy Gear**	**Faulty Gear**
01	RMS	0.8751	0.8827
02	Variance	0.7658	0.7791
03	Kurtosis	2.2693	2.3515
04	Skewness	-6.88x10^-4	0.0412
05	Peak to RMS	2.8901	3.6370

4. Conclusion

The popularity of vibration-based machine condition monitoring is increasing day by day. The simulation-based TSA approach presented in this paper shows how the faulty signal can be distinguished in the time-domain analysis. The quantitative comparison based on the statistical parameter also provides significant differences between the signal of healthy gear and faulty gear. Skewness identifies the asymmetric behavior of vibration signals using its probability density function provides a significant difference. Peak to RMS also shows promising characteristics differences.

5. References

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