Fault Detection in Bevel Gear Using Condition Indicators

Mahendra Singh Raghav, Rahul Tiwari, and Ram Bihari Sharma

1 Introduction

Condition-based maintenance plays a vital role in minimizing unplanned downtime of machinery and preventing serious accidents in industrial companies. The most widely used technique, for fault detection in gearboxes, is vibration analysis. The vibration signals are measured using an accelerometer. The conventional techniques used for processing measured data are divided into three domains, viz., frequency domain, time domain and time–frequency domain. In this paper, condition indicators based on time-domain signals are used for diagnosing faults in bevel gear.

The bevel gear is the main components of the power transmission system in a rotorcraft. An enormous amount of research work has been carried out on condition monitoring of different types of gearboxes. However, a minimal amount of research work is available on condition monitoring of bevel gears. Statistical indicators are very promising tools for diagnosis of faults in gears [1–3]. Ozturk et al. [4] claimed that root-mean-square (RMS), peak to peak, kurtosis, crest factor and cepstrum analysis could expose extremely severe faults only. Zhao et al. [5] extracted 252 fault features for classification of fault in gear with a different level of severity of pitting. Dempsey et al. [6] used FM4 and NA4 for detecting natural gear pitting, while Lin et al. [7] proposed a parameter grounded on residual error signal called the fault growth parameter (FGP). Elasha et al. [8] in addition to RMS, Kurtosis and FM4 also applied to envelop and Spectral Kurtosis (SK) for detecting pitting phenomenon

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in worm gear and found that pitting in worm gear can be easily detected using FM4 and SK. Combet et al. [9] also applied SK to detect pitting at an early stage. Kundu et al. [10] proposed a correlation coefficient-based fault detection, and the correlation coefficient of residual signal (CCR) of faulty gear was compared with CCR of healthy gear. Ahmed et al. [11] calculated RMS, crest factor and kurtosis over a multiple-pulse individually rescaled-time synchronous averaging (MIR-TSA) signal. They claimed the fault detection capability of RMS was enhanced. Wang et al. [12] presented the instantaneous time–frequency spectrum constructed by local mean decomposition. They also proposed the energy dispersion ratio as a new parameter which is sensitive to deterioration scenarios of low-speed helical gearboxes.

In the present work, statistical parameters are applied on vibration signals to identify faults in bevel gear. Five statistical indicators, i.e., RMS, crest factor, kurtosis, peak to peak and skewness, have been implemented on the signal acquired from the bevel gearbox.

2 Statistical Indicators

The statistical parameters used in this study are described as follows:

(i) **RMS**: It shows the energy and amplitude of the vibration signal in the time domain. The RMS value can be obtained by calculating the summation of the squares of the signal samples, and then the square root of the average of the sum [13], and it is expressed as

$$\mathrm{RMS} = \sqrt{\frac{1}{N}\left[\sum_{i=1}^{N}(x_i)^2\right]} \tag{1}$$

where x_{i} is the ith sample of the signal and N is the total number of samples.

(ii) **Crest Factor**: The ratio of the magnitude of the peak value of the signal to RMS value of the signal is called the crest factor [13] and is given by

$$\mathrm{CF} = \frac{x_{0-pk}}{\mathrm{rms}_x} \tag{2}$$

where pk is the sample for the peak value of the signal and $x_{0\text{-}pk}$ is the magnitude of the peak value of x at pk. Crest factor has no unit.

(iii) **Kurtosis**: Kurtosis can be defined as the fourth-order normalized moment of a signal. It gives a measurement of significant peaks of a signal, i.e., the number and amplitude of peaks existent in the signal [13, 14]. It is given by

$$K = \frac{N \sum_i^N (x_i - \overline{x})^4}{\left(\sum_i^N (x_i - \overline{x}^2\right)^2} \tag{3}$$

The kurtosis value of a Gaussian-like signal is close to 3. A gearbox in healthy condition is associated with the Gaussian distribution of samples of the signal.

(iv) **Skewness**: Skewness is the third statistical moment, and it is a measure of the asymmetry of the probability density function of the samples of the signal [13]. The following equation can express it:

$$s = \frac{n}{(n-1)(n-2)} \sum \left(\frac{x_i - \overline{x}}{s} \right)^3 \tag{4}$$

(v) **Peak to peak**: This statistical parameter can be defined as the difference between maximum and minimum amplitudes [13]. It may be given as follows:

$$p2p = x_{\max} - x_{\min} \tag{5}$$

3 Experimental Setup and Data Acquisition

The experimental study was conducted on machine fault simulator, as shown in Fig. 1. The test setup includes 1HP AC motor, a single-stage straight bevel gearbox, rotor shaft and motor controller. AC motor with a maximum speed of 3600 rpm is

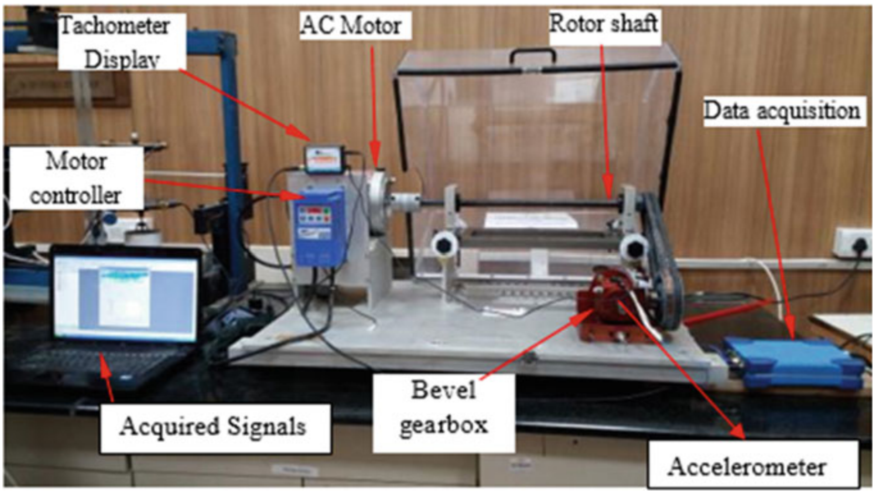


Fig. 1 Experimental setup and data acquisition system

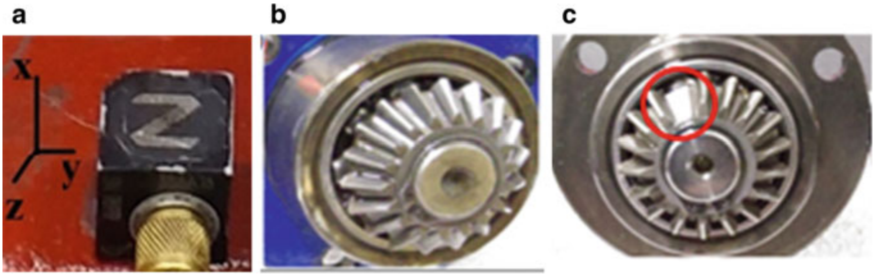


Fig. 2 **a** Zoomed view of the accelerometer, **b** healthy bevel gear and **c** missing tooth bevel gear

Table 1 Specifications of a gearbox

Gear ratio	1.5:1
Pitch angle (gear)	56°19′
Pitch angle (pinion)	33°41′
Pressure angle for gear and pinion	20°
Number of teeth in pinion	18
Number of teeth in a gear	27

connected to a rotor shaft. The input shaft of the bevel gearbox is connected to a rotor shaft via a belt drive to reduce the effect of vibration of an electric motor on the gearbox. An ICP-type triaxial accelerometer, with a range of 0.5 Hz to 5 kHz, is mounted on a housing of the gearbox as shown in Fig. 1. Figure 2a shows the enlarged view of accelerometer, and Fig. 2b, c shows the healthy and faulty bevel gear. An OROS OR34 data acquisition system with a maximum sampling rate of 52 k samples/s is used to acquire data from the sensor. The acquired data is recorded and processed using NVGate. The specifications of gears are mentioned in Table 1.

The tests were conducted at a constant input shaft speed of 420 rpm. The motor controller, as shown in Fig. 1, is used to run the motor at a constant speed of 420 rpm. The vibration signals were recorded for a healthy gear at 0 to 4 N load. The load is applied on gearbox using a magnetic controller attached to the output shaft of the gearbox. The vibration signals were recorded in all three directions, but signals from x-direction, i.e., horizontal radial direction, are used. Five samples of signals for a duration of 1.6 s, each with a sampling rate of 6400 samples, were recorded at all loading conditions. The tests were repeated with missing tooth gear also.

4 Results and Discussion

Figures 3 and 4 show the vibration signal of healthy bevel gear and gear with a missing tooth at 0–4 N load. The amplitude for the bevel gear with a missing tooth, as shown in Fig. 4, is higher than the amplitude for healthy gear at all load conditions.

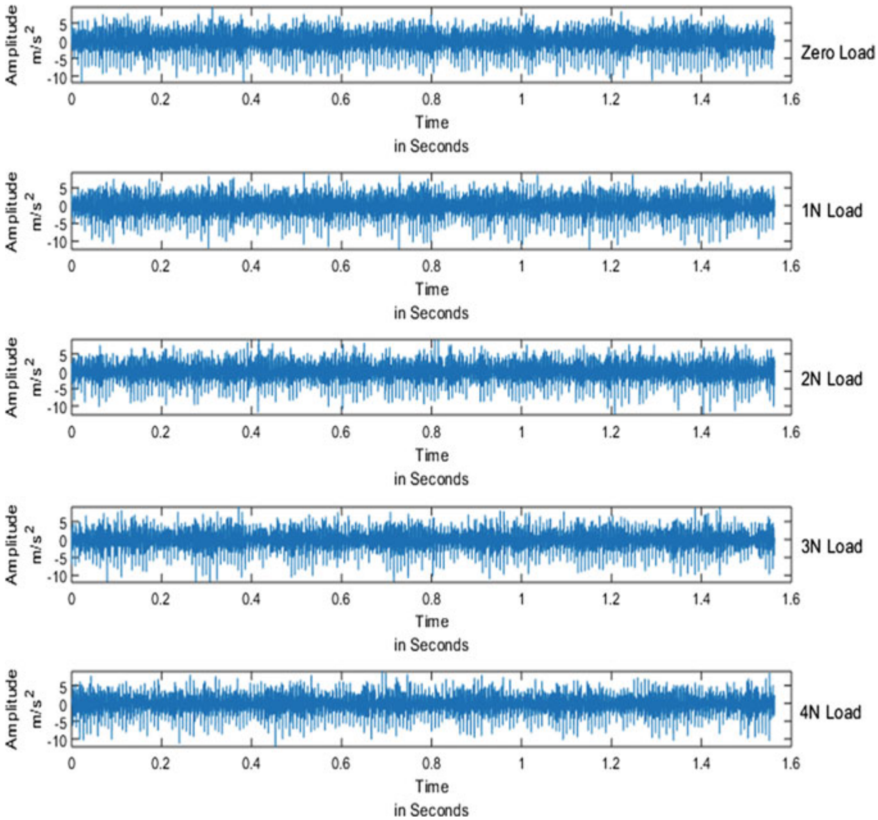


Fig. 3 Healthy bevel gear vibration signal at a constant speed of 420 rpm

It can be easily observed that the load has little effect on the amplitude of the vibration signal. The time-domain signals are converted in the frequency domain using fast Fourier transform (FFT). Figures 5 and 6 show the FFT of vibration signals of missing tooth bevel gear and healthy bevel gear, respectively. The gear mesh frequency (GMF) and its harmonics are visible in all cases. The amplitude of GMF and its harmonics do not show any increasing trend with the increase in load. However, in case of missing tooth gear, the amplitude of GMF and its harmonics are higher at all load conditions than that of healthy gear. It can be observed that the amplitude of sidebands is also higher in the case of missing tooth gear.

The statistical indicators, i.e., RMS, crest factor, peak to peak, kurtosis and skewness, were calculated over the acquired vibration signals, and the values obtained are shown in Fig. 7. The energy of the vibration signal of missing tooth gear is higher than healthy gear at all load condition, as indicated by RMS. The value of the crest factor for missing tooth gear is varying from 12 to 16. When the value of the crest factor exceeds 6, it indicates the possibility of fault in gear [15]. The kurtosis value

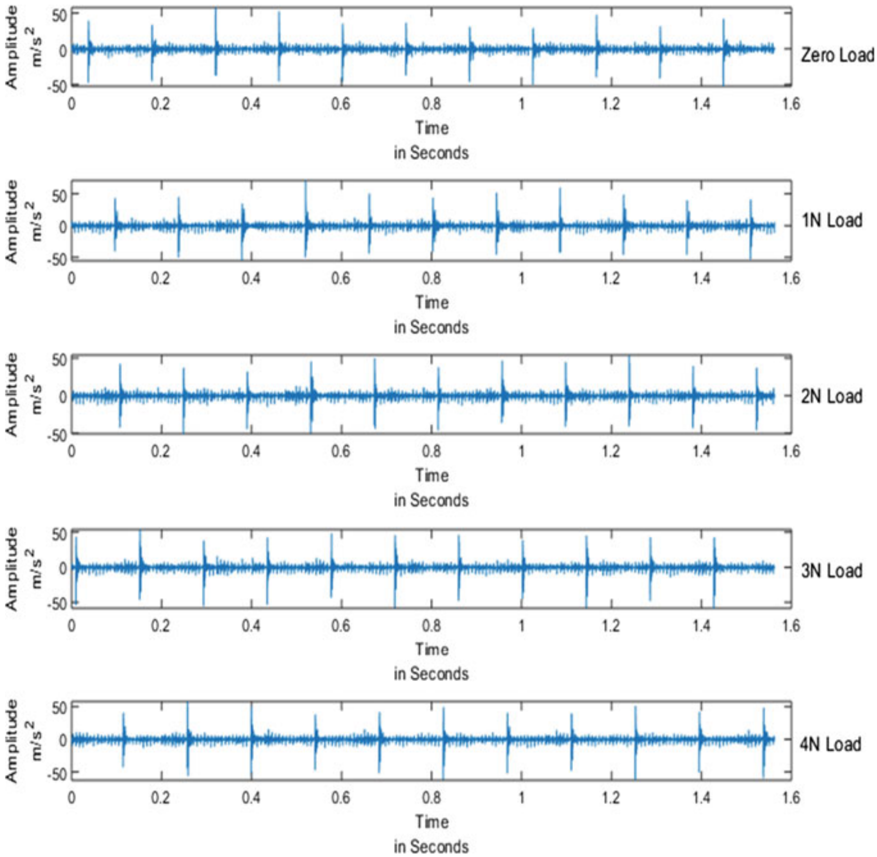


Fig. 4 Bevel gear vibration signal with a missing tooth at a constant speed of 420 rpm

of healthy gear vibration signal is around 3 for all load condition which is a confirmation of a healthy state [14]. However, in the case of missing tooth gear, kurtosis value lies in the range of 35–45. Kurtosis value of higher than 3 is a clear indication of faulty gear. Peak to peak also suggests that the value of peaks is higher at all load conditions due to the presence of missing tooth fault in the bevel gear. These parameters identify the missing tooth gear fault except skewness.

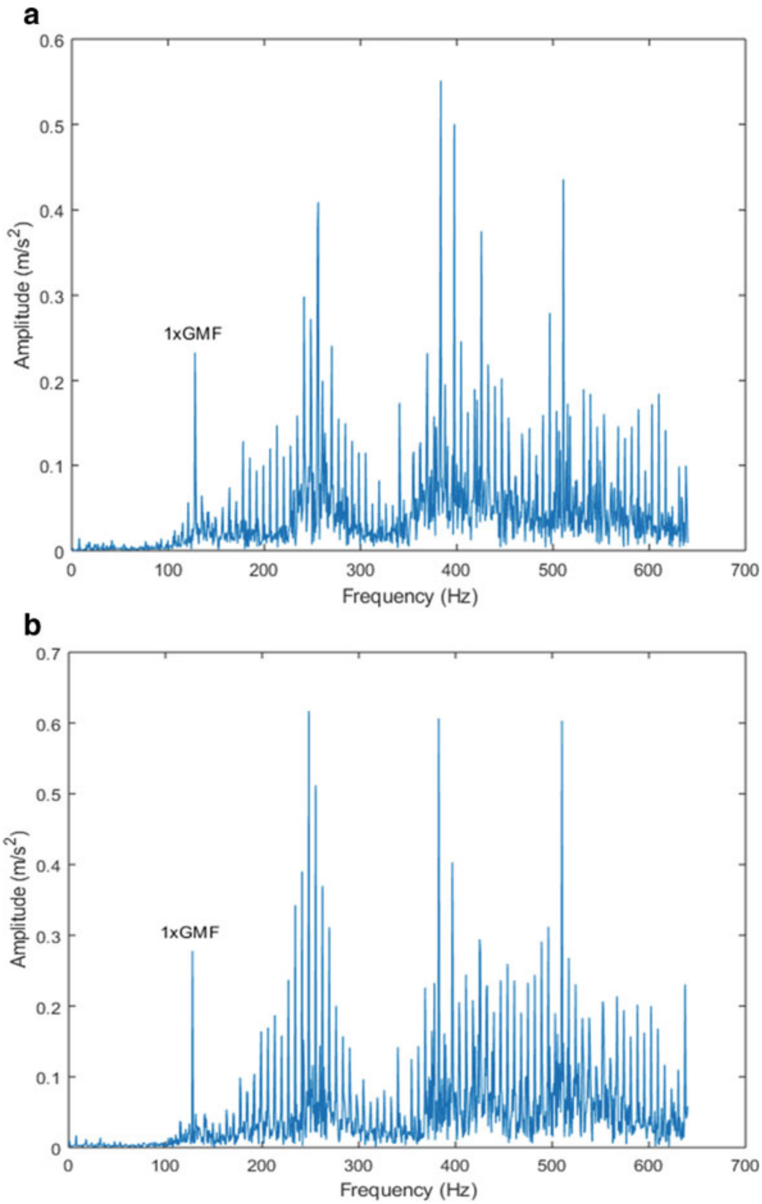
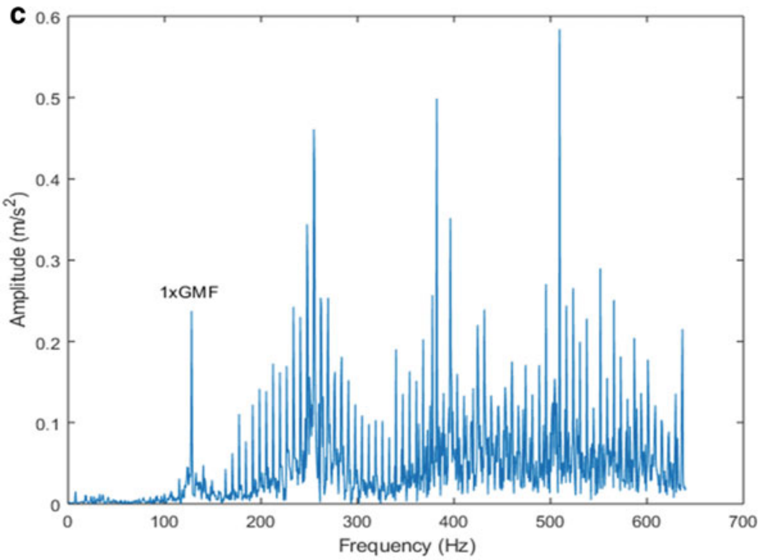


Fig. 5 FFT of missing tooth vibration signal at **a** zero load, **b** 1 N load, **c** 2 N load, **d** 3 N load and **e** 4 N load



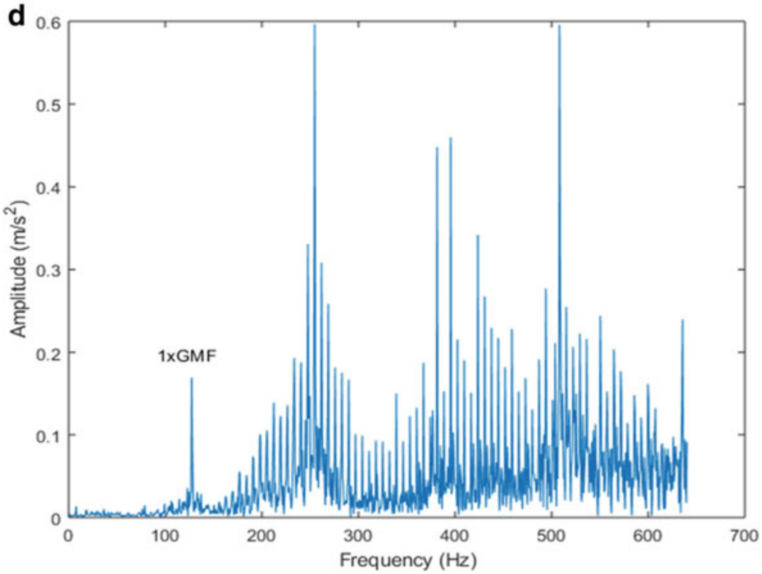
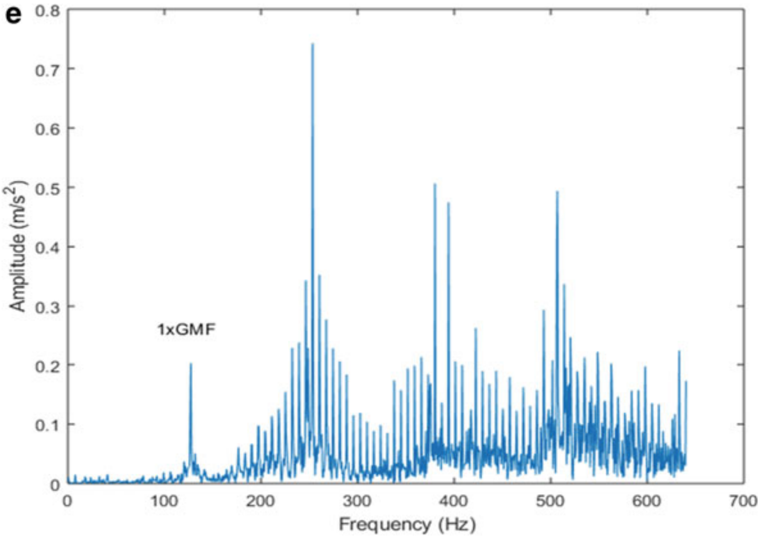


Fig. 5 (continued)



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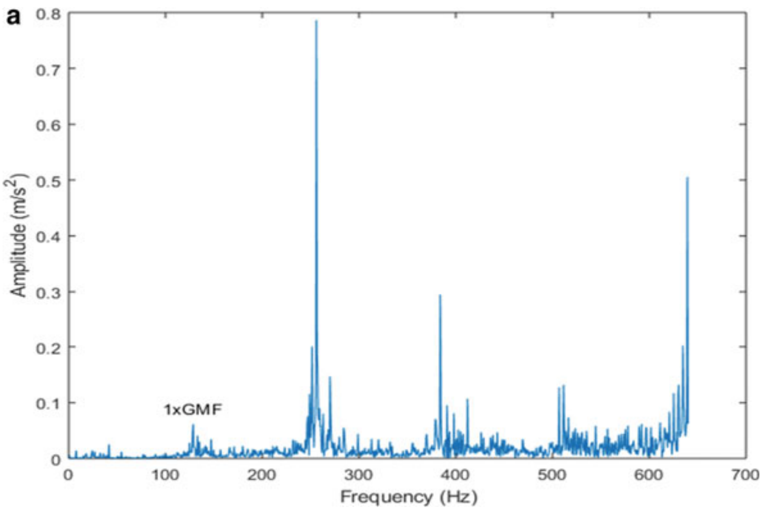

Fig. 6 FFT of healthy gear vibration signal at **a** zero load, **b** 1 N load, **c** 2 N load, **d** 3 N load and **e** 4 N load

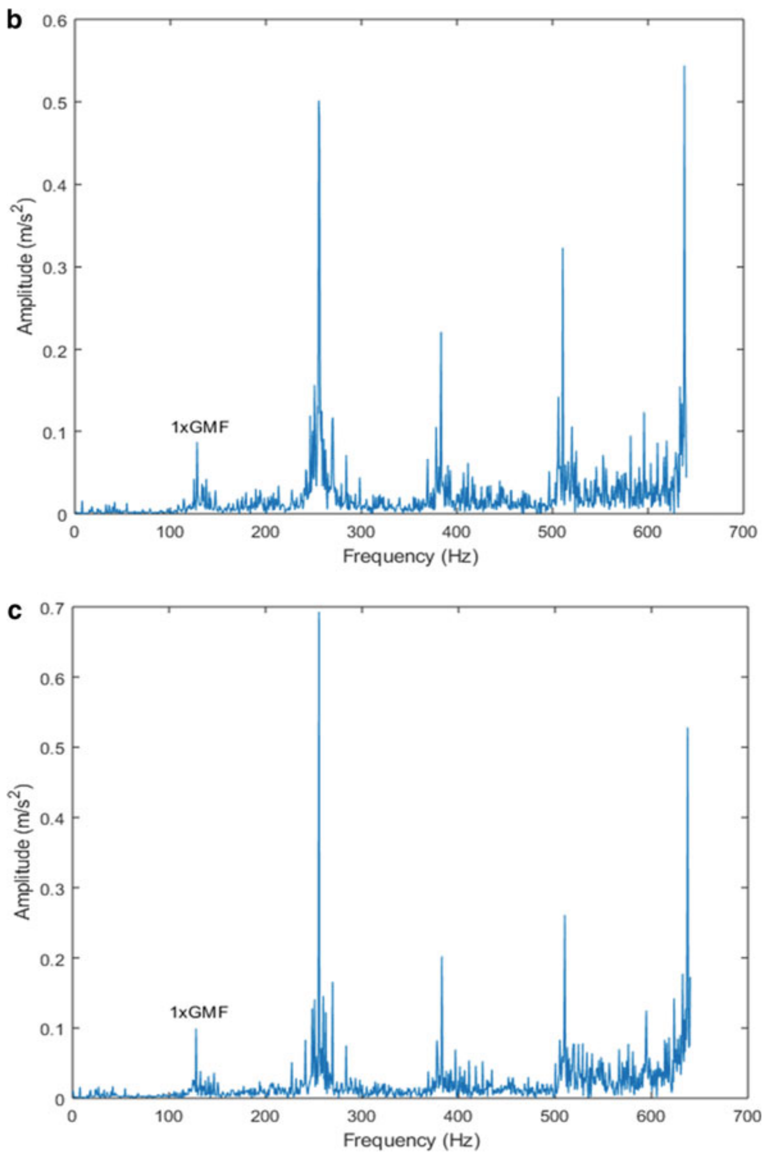

Fig. 6 (continued)

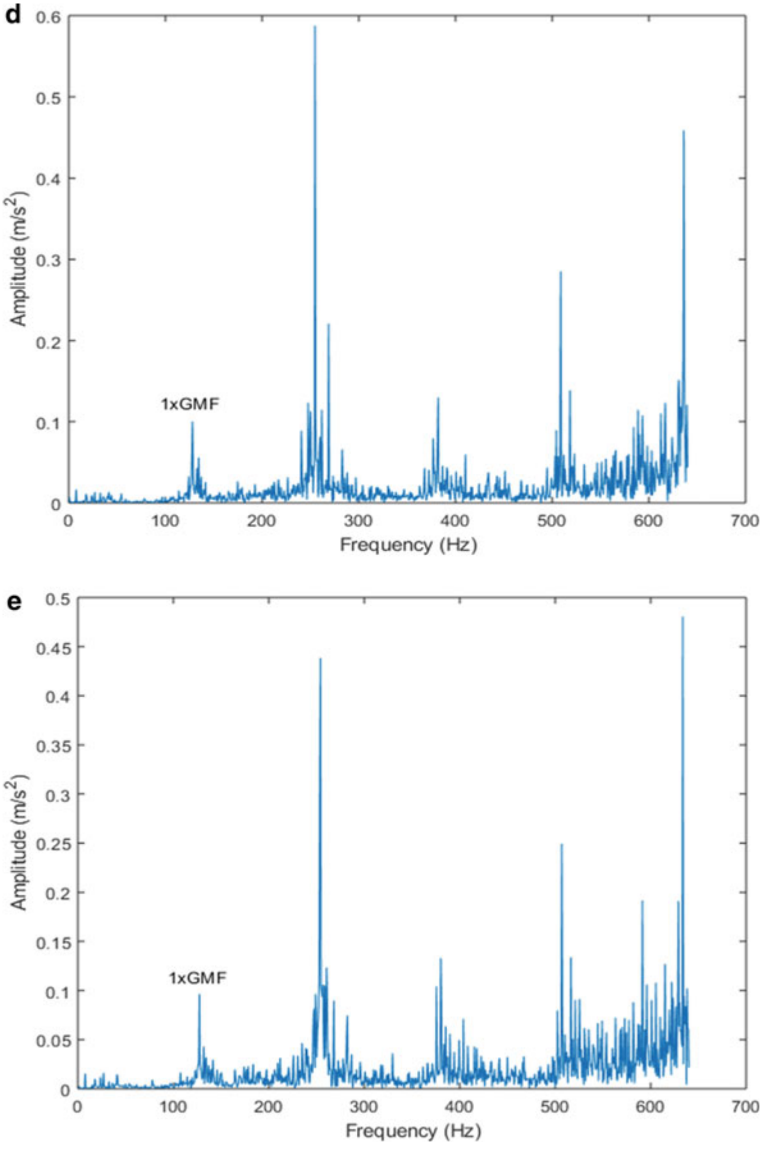

Fig. 6 (continued)

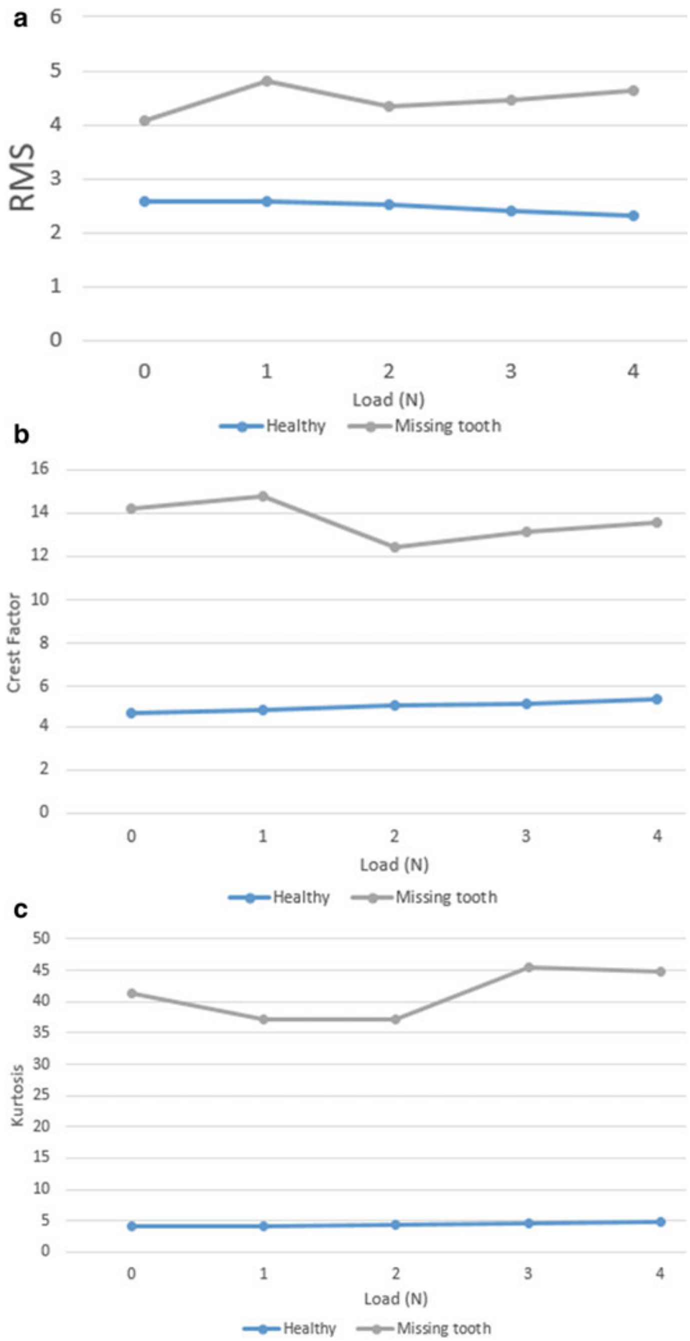

Fig. 7 Statistical parameters: **a** RMS, **b** crest factor, **c** kurtosis, **d** peak to peak and **e** skewness

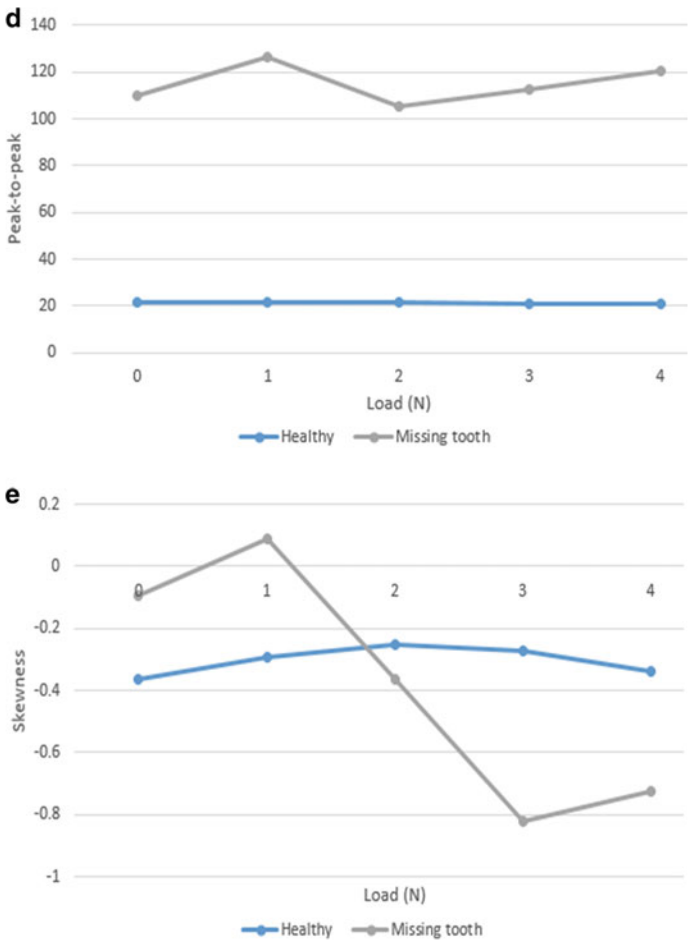

Fig. 7 (continued)

5 Conclusions

In the present work, an experimental study on fault diagnosis of bevel gear is presented. Statistical parameters are used over vibration signals acquired from missing tooth and healthy bevel gear. It is found that missing tooth fault can be easily identified using RMS, kurtosis, crest factor and peak to peak except for skewness.

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