Fault Diagnosis of Gearbox Using Various Condition Monitoring Indicators for Non-Stationary Speed Conditions: A Comparative Analysis

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Abstract

Statistical indicators are widely used for the condition monitoring of the gearbox. Fault diagnosis of gearbox at the initiation of crack is very important before it get turned into catastrophe. These condition monitoring indicators are applied to the signal acquired from the gearboxes via accelerometers. Every indicator has own capabilities to identify the fault and gives alarm during crack propagation. But, in the bunch of indicators which is most worthy and sensitive toward fault is still not clear? So this study shows a widespread comparison between RMS, Kurtosis, Crest Factor, FM0, FM4, M6, NB4, Energy ratio, NA4, Energy operator, performed for no crack, initial crack and advanced crack on pinion with different fluctuating input speeds. In real time situations, machines like gearboxes observe various types of fluctuations like sinusoidal speed fluctuation, quadratic speed fluctuations and random speed fluctuation. Experiments are performed on gearbox test rig; signals are acquired at different input speed profiles to test the performance of statistical indicators. This comparative analysis shows the responsiveness of indicators towards crack. Result suggests that statistical indicators are more prone to fluctuating speed, but not towards crack.

Keywords: Fault diagnosis, condition monitoring indicators, gear fault, fluctuating speed.

1 Introduction

Vibration based fault detection techniques have been used to know early failures appearing in gearbox [1]. Fundamentally, vibration signal is a compound signal which contains shaft frequency and its harmonics, tooth meshing frequency and its harmonics, fault transients and unwanted noise appearing due to meshing of gears and friction in between the parts. In a broad context, analysis of the gear vibration signal can be done by using time domain techniques [2], frequency domain techniques [3] and time-frequency techniques [4]. Condition monitoring indicators (CI) are also used to compute the level of vibrations generated because of appearing fault phenomenon [5], [6]. By means of these indicators some fault modes such as pitting crack and wear were observed on gears in gearbox. Moreover, it has been shown that statistical analysis performed using RMS, kurtosis, FM4 and NB4 of signal provides alarm about incipient fault of raw signal [7]-[9] where kurtosis, FM4, NB4 value increases more than nominal value which indicates presence of fault.

In this paper a comparative analysis of CIs for various crack detection has been done**.** A crack has been simulated on pinion tooth root as suggested by Pandya and Parey [10]. The experimental setup of drivetrain diagnostic simulator is briefly introduced and the information about the experimental investigation for the cracked pinion with different fluctuating speed cases and crack specification has been demonstrated in later sections. At the end, results of the present study have been presented and concluded.

2 Condition monitoring indicators

The following are the condition monitoring indicators which have been used in the present study

2.1 R.M.S.

It signifies the energy content within a signal with respected to time. The root mean squared (rms) is defined as the square root of the mean of the sum of the squares of signal samples [9] and is given by

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

Where, x is the original sampled time signal N is the number of samples and i is the sample index.

2.2 Kurtosis

It is the fourth order moment normalized by the square of variance of a signal x and gives a measure of the peakedness of the signal [9]. It is given by

$$K = \frac{N\sum_{i=1}^{N}(x_i-\bar{x})^4}{\left(\sum_{i=1}^{N}(x_i-\bar{x})^2\right)^2} \quad (2)$$

For a healthy gear vibration signal, kurtosis is approximately 3.

2.3 Crest Factor

The crest factor (CF) is defined as the ratio of maximum positive peak value of the signal x to RMS_x [9] and is given by

$$CF = \frac{x_{0-pk}}{rms_x} \quad (3)$$

Where, pk is the sample for the maximum positive peak of the signal and x_{0-pk} is the value of x at pk.

2.4 Zero Order Figure of Merit (FM0)

It is an indicator of major faults in a gear mesh [[9]]. Changes in the meshing pattern can be noticed by comparing the maximum peak-to-peak amplitude of the signal to the sum of the amplitudes of the mesh frequencies and their harmonics. It is given as

$$FM0 = \frac{PP_x}{\sum_{N=0}^{H} P_N} \quad (4)$$

Where, PP_x is the maximum peak-to-peak amplitude of the signal x; P_N is the amplitude of the N^{th} harmonic, and H is the total number of harmonics in the frequency spectrum.

2.5 Fourth Order Figure of Merit (FM4)

It was designed to boost FM0 by detecting faults isolated to only a finite number of gear teeth [[8]]. This is done by first constructing the difference signal, d (The removal of gear meshing frequency, its harmonics and its first order harmonics from time synchronous average signal (TSA) is called difference signal) and then normalized kurtosis of d is then computed as

$$\mathrm{FM4} = \frac{\mathrm{N}\sum_{\mathrm{i}=1}^{\mathrm{N}}(\mathrm{d_i}-\bar{\mathrm{d}})^4}{\left(\sum_{\mathrm{i}=1}^{\mathrm{N}}(\mathrm{d_i}-\bar{\mathrm{d}})^2\right)^2} \tag{5}$$

Where, $\bar{\mathrm{d}}$ is the mean of the difference signal, and N is the total number of data points in the time signal.

2.6 M6A

The parameter M6A was proposed by Martin in 1989 [8] as surface damage indicator for machinery components. The fundamental idea is the same as that of FM4, only the moment is normalized by the cube of the variance. However, it is expected that M6A will be more sensitive to peaks in the difference signal because of using sixth moment. M6A is given as

$$\mathrm{M6A} = \frac{\mathrm{N}^2\sum_{\mathrm{i}=1}^{\mathrm{N}}(\mathrm{d_i}-\bar{\mathrm{d}})^6}{\left(\sum_{\mathrm{i}=1}^{\mathrm{N}}(\mathrm{d_i}-\bar{\mathrm{d}})^2\right)^3} \tag{6}$$

2.7 NB4

It was developed in 1994 by Zakrajsek, Handschuh and Decker [11] to indicate localized gear tooth fault. The hypothesis behind NB4 is that fault within a few teeth will create transient load fluctuations dissimilar to those load fluctuations caused by healthy teeth and this can be observed in the envelope of the signal. NB4 uses the quasi-normalized kurtosis of the envelope of the signal bandpass filtered about the mesh frequency. The envelope, s(t) is computed using the Hilbert transform and is given by

$$\mathrm{s(t)} = \left|\left[\mathrm{b(t)} + \mathrm{i}[\mathrm{H}(\mathrm{b(t)})]\right]\right| \tag{7}$$

Where, $\mathrm{b(t)}$ is the band-pass filtered signal about the mesh frequency, $\mathrm{H(b(t))}$ is the Hilbert transform of $\mathrm{b(t)}$; and i is the sample.

2.8 Energy Ratio

It is a ratio of RMS of the difference signal d to the RMS of the signal containing only the regular meshing components, $\mathrm{y_d}$ and is given by [12]

$$\mathrm{ER} = \frac{\mathrm{RMS_d}}{\mathrm{RMS_{y_d}}} \tag{8}$$

2.9 Energy Operator (EOP)

An impulse in time averaged vibration signal initiated by damaged gear tooth supported by energy operator, thus allowing the impulse to be more easily detected [13].

$$\text{EOP} = \frac{N\sum_{i=1}^{N}(re_i-\overline{re})^4}{\left(\sum_{i=1}^{N}(re_i-\overline{re})^2\right)^2} \quad (9)$$

Where, where re_i equals $x_i^2 - x_{i-1}x_{i+1}$ and it is the i^{th} measurement of the resulting signal re, and $\overline{re}$ is the average of the resulting signal. EOP is developed by first calculating the value $x_i^2 - x_{i-1}x_{i+1}$ for every point x_i $(i = 1, \ldots, N)$, of the signal. At the end points, the signal is assumed to be a continuous loop. The energy operator is then computed by taking the kurtosis of the resulting signal.

2.10 NA4

It was developed as a general fault indicator reacting to both damage and continuing growth of the fault [11]. The quasi-normalized kurtosis of the residual signal (The removal of regular gear meshing harmonics from TSA is called residual signal) is calculated by obtaining a ratio of fourth moment of the residual signal to the square of its run time averaged variance. The mean variance is the average value of the variance of all earlier data records in the run ensemble. NA4 is given as

$$\text{NA4}(M) = \frac{N\sum_{i=1}^{N}(r_{iM}-\bar{r}_M)^4}{\left(\frac{1}{M}\sum_{j=1}^{M}\left(\sum_{i=1}^{N}(r_{ij}-\bar{r}_j)^2\right)\right)^2} \quad (10)$$

Where, $\bar{r}$ is the mean of the residual signal, N is the total number of data points in the time signal, M is the number of the current time signal, and j is the index of the time signal in the run ensemble.

3 Experimental evaluation

3.1 Experimental setup

The vibration signals were documented from the drivetrain dynamic simulator (DDS). Figure 1, depicts the experimental setup of gear test rig. It is a motor-drive-brake test setup using a 2.237 kW, 3 phase, 0-3000 rpm for variable speed operation and load is applied by magnetic particle brake with a pinion and a gear of $14\frac{1}{2}$ degree pressure angle. The center distance between gearbox shafts is 89 ± 1mm.

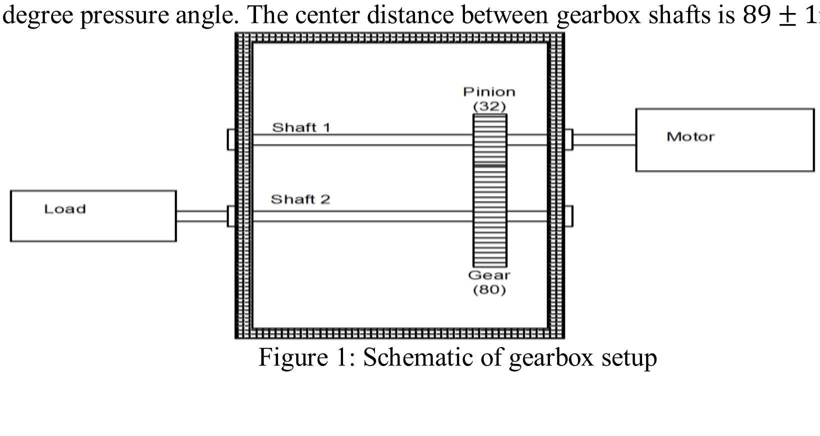


Figure 1: Schematic of gearbox setup

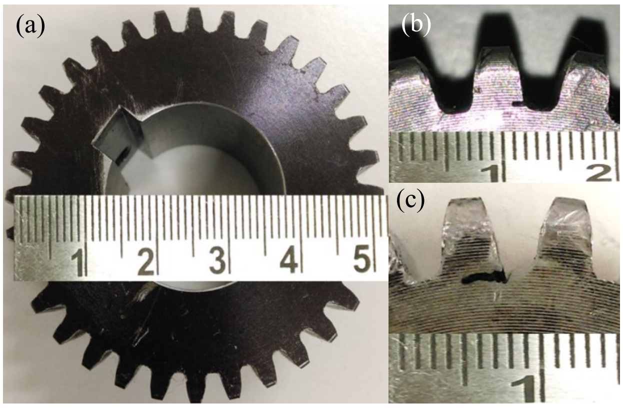


Figure 2: Pinion with various gear tooth health and crack size

Two cracks have been generated on pinion, as shown in Figure 2; initial crack of 1 mm and up to 3 mm for advanced crack. In this paper, a method for the detecting faults in rotational drives viz. gearboxes subjected to variable operating speed conditions is being presented. The non-stationary behaviour of speed can be considered by operating the motor. The generated vibration from the speed variability is a challenge in the fault detection.

3.2 Non-stationary speed conditions

In real-time environment the speed doesn’t remain constant, it obeys non-stationary speed conditions. These non-stationary fluctuations may appear in any fashion. Various fluctuating input speed profiles are found in the literature [14], [15].

3.2.1 Constant speed

In first case, constant speed is considered of the input shaft. The vibration signals for the different gear crack conditions are shown below in Figure 3

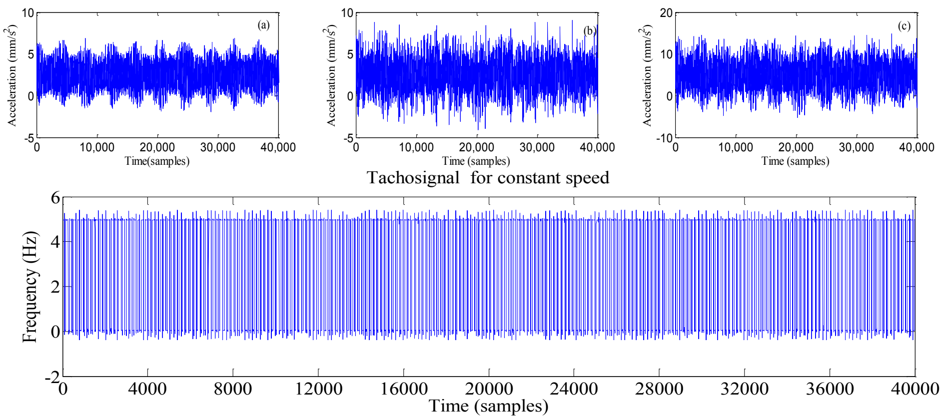


Figure 3: Gearbox signal for constant speed (a) healthy gear vibration signal, (b) vibration signal with initial fault, (c) vibration signal with advanced fault.

3.2.2 Sinusoidal fluctuating speed

The second case is of sinusoidal speed fluctuation of the input shaft. The vibration signals for the different gear crack conditions and speed fluctuation are shown below in Figure 4.

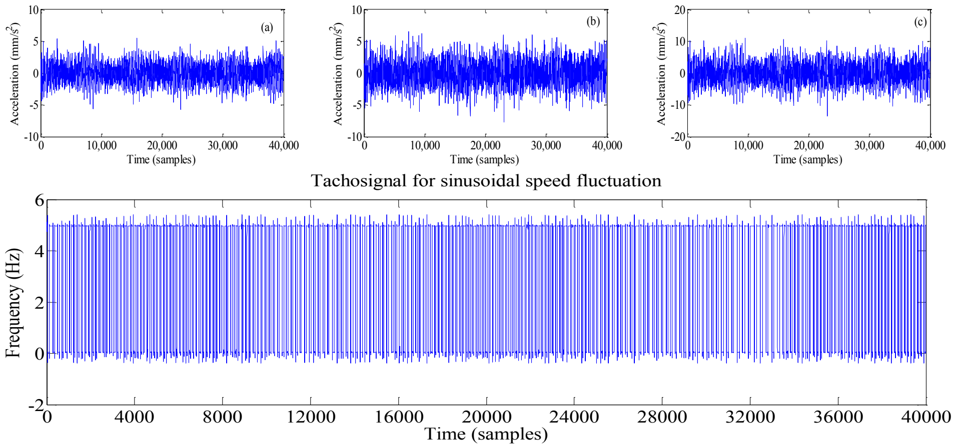


Figure 4: Gearbox signal for sinusoidal speed fluctuation (a) healthy gear vibration signal, (b) vibration signal with initial fault, (c) vibration signal with advanced fault.

3.2.3 Quadratically fluctuating speed

The third case is of quadratically speed fluctuation of the input shaft. The vibration signals for the different gear crack conditions and speed fluctuation are shown below in Figure 5.

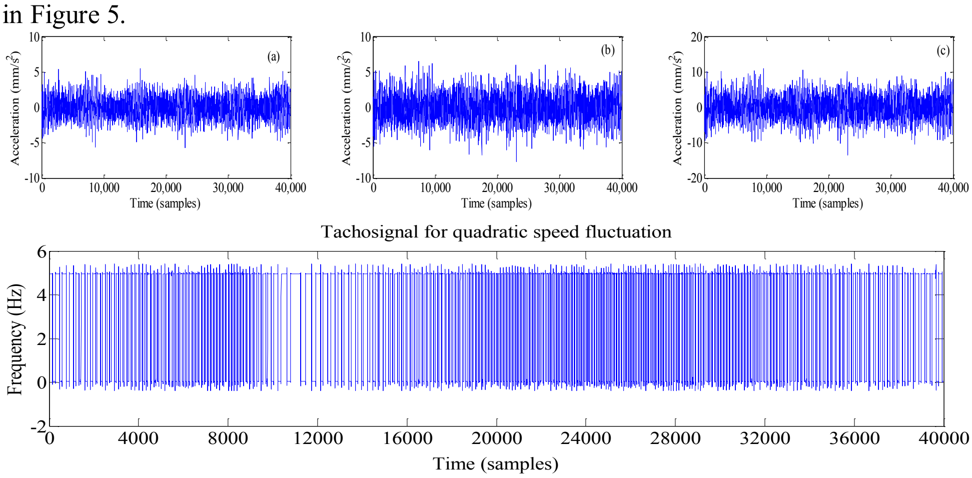


Figure 5: Gearbox signal for quadratic speed fluctuation (a) healthy gear vibration signal, (b) vibration signal with initial fault, (c) vibration signal with advanced fault.

4 Evaluation of CI

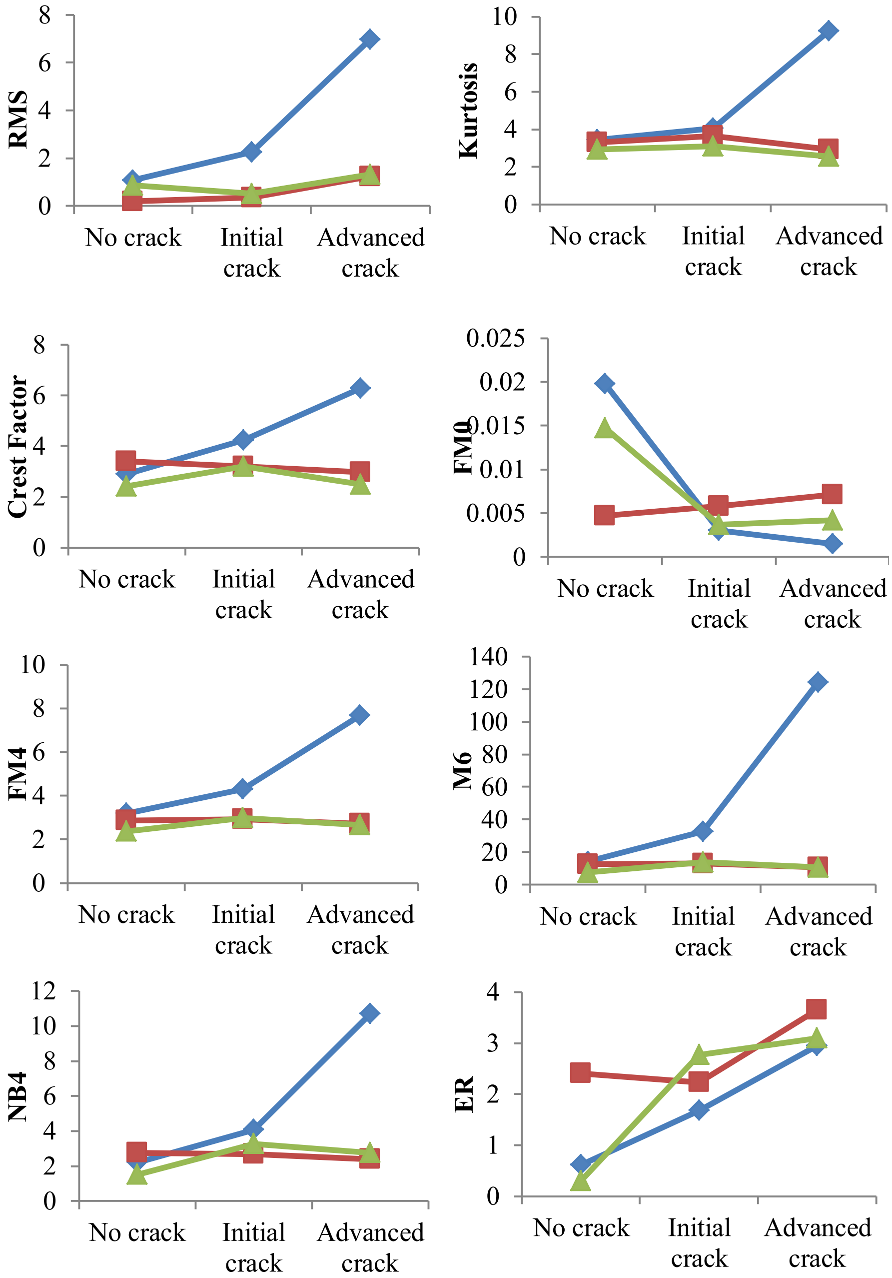
CI for different gear health and speed fluctuation cases has been evaluated for time domain signals. Values of various time domain CIs have been tabulated in Table 1.

Table 1: Time domain condition monitoring indicators

Features	*Gear health conditions*			*% increase*	
	No crack	*Initial crack*	*Advanced crack*	*Initial crack*	*Advanced crack*
(a) constant input speed					
RMS	1.086	2.245	6.967	106.646	541.379
Kurtosis	3.440	4.060	9.243	18.028	168.732
Crest Factor	2.892	4.236	6.288	46.483	117.427
FM0	0.020	0.003	0.002	-84.848	-92.424
FM4	3.184	4.295	7.659	34.913	140.574
M6	14.096	32.556	124.064	130.961	780.138
NB4	2.222	4.086	10.674	83.903	380.474
ER	0.608	1.675	2.944	175.403	384.035
EOP	3.622	11.109	38.373	206.670	959.334
NA4	3.041	4.155	4.788	36.647	57.437
(b) sinusoidally fluctuating input speed					
RMS	0.195	0.351	1.247	80.390	540.349
Kurtosis	3.299	3.651	2.932	10.648	-11.136
Crest Factor	3.413	3.191	2.980	-6.496	-12.690
FM0	0.005	0.006	0.007	23.404	51.064
FM4	2.866	2.933	2.727	2.338	-4.840
M6	12.760	13.118	10.545	2.810	-17.360
NB4	2.770	2.685	2.396	-3.083	-13.498
ER	2.406	2.227	3.647	-7.472	51.577
EOP	8.552	10.796	7.227	26.246	-15.491
NA4	4.158	4.713	3.170	13.349	-23.772
(c) quadratically fluctuating input speed					
RMS	0.865	0.517	1.328	-40.187	53.626
Kurtosis	2.920	3.112	2.551	6.579	-12.654
Crest Factor	2.422	3.209	2.505	32.490	3.443
FM0	0.015	0.004	0.004	-74.830	-71.429
FM4	2.357	2.978	2.649	26.348	12.383
M6	7.509	13.658	10.621	81.887	41.448
NB4	1.495	3.270	2.769	118.738	85.249
ER	0.305	2.776	3.100	809.833	916.060
EOP	6.066	7.763	6.165	27.978	1.634

NA4	2.067	3.679	3.103	78.045	50.133

Figure 6, shows the performance analysis of various statistical indicators for different input speed conditions and gear health condition (i.e., no crack, initial crack and advanced crack).



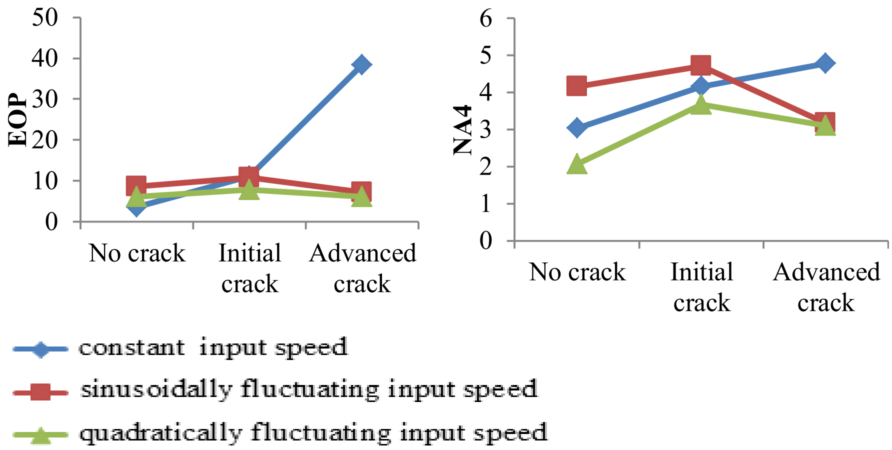


Figure 6: Variation of statistical indicators for different input speed and gear health conditions

4.1 Performance of condition indicators

A comparative analysis of various CI which are used by many researchers for the gear fault diagnosis under the constant or variable operating conditions has been shown here. It can be inferred from Figure 6, that for the case of constant input speed, all the indicators are working well showing increasing patterns, whereas FM0 is sinking. M6 and EOP are more responsive towards fault for constant speed. For the case of sinusoidal speed fluctuation, kurtosis, FM4, CF, M6, NB4, EOP and NA4 are not showing the increasing trends for increasing gear crack. Similarly, rms and energy ratio are failing to show response towards initial crack for the case of quadratic speed fluctuation.

The responses of pre-existing statistical indicators varies for gear crack conditions and are not appearing in same fashion, hence can be considered unsusceptible to fault diagnosis prospects with fluctuating input speeds.

5 Conclusions

In this paper, experiments have been performed for various gear tooth conditions at different fluctuating speeds. A comparative study of RMS, Kurtosis, Crest Factor, FM0, FM4, M6, NB4, Energy ratio, NA4, Energy operator, has been done for no, initial and advanced crack on pinion. This study highlights that the most of the indicators are responsive to speed fluctuations and insensitive to fault diagnosis for fluctuations in input speed. Foe constant speed, all indicators works well except FM0.

Furthermore, these indicators need to be evaluated for the non-stationary loading condition which is going to be the next objective in the area of non-stationary signals with non-constant working conditions. Even for the various successive order of crack lengths can also be focused or different fault can be used for performance analysis of these indicators. As a result of this study there is a need of statistical indicator or an effective method to diagnose the fault at non-stationary speed conditions.

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