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# A review of gear fault diagnosis using various condition indicators

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**Abstract**

Plentiful work has been done for condition monitoring (CI) and fault diagnosis of fixed-axis gearboxes. However, still it is found that articles citing condition indicators for fault diagnosis of gearboxes are less in quantity, in academic journals, conference proceedings and technical reports. The specialty of condition indicators is to provide accurate information regarding the condition of various components at different levels of damage (initial, heavy or growing). Here, these indicators are addressed domain-wise and their characteristics are stated. The objective of this paper is to review and encapsulate this literature to provide a wide and good reference for researchers to be utilized. The structure of a fixed-axis gearbox is briefly introduced. The unique behaviors and fault characteristics of fixed-axis gearbox is recognized and studied. Investigations on the basis of statistical indicators are also summarized based on the adopted methodologies. Lastly, open problems are stated and further research prospects pointed out.


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*Keywords:* Fixed-axis gearboxes; fault diagnosis;condition indicators; gear fault;signal processing;

## 1. Introduction

Over more than two decade, huge emphasis is given to research on vibration based fault diagnosis methodologies [1]-[4] that are applied to vibration signals acquired from gearboxes via transducers mounted on gearbox casing. The output of these techniques is to identify changes in the signal caused due to damaged parts. Modulations appear within gearbox, because gearboxes mostly operate under rough working environment. Their basic components, for ex. gears and bearings, are subject to damage modes such as fatigue crack, pitting, scaling [5],[6]. Even a small failure could lead to a catastrophe, therefore condition monitoring and fault diagnosis systems should be planted in a

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machine to raise alarm thereby avoiding accidents and generate cost savings. Most of the studies focus on fixed-axes gearboxes in which all gears rotate around their own fixed centres. Also, information of fault has been finding out by the use of statistical analysis of vibration signal [7]. Compared to vibration based techniques, studies on condition indicators (CI) for fault diagnosis of gearboxes are limited. In 2005, Samuel and Pines [8]and in 2014 Lei et al. [9], thoroughly reviewed vibration based diagnostic techniques for a planetary gearbox, while a review specifically focusing on statistical indicators for fault diagnosis of gearboxes has not been reported yet on the basis of authors' literature search. This paper aims to encapsulate and survey the research and development of CI for fault diagnosis of gearboxes. It is to blend the individual pieces of work on this topic in context to gearboxes. An attempt has been made to provide a broad reference for researchers and helping them to develop advanced research topics in this area.

The plot of the paper is organized as follows. Section 2, briefly explains fixed-axis gearboxes, characteristic frequency and statistical measurement for fault detection. Section3 reviews the publications on CIs according to the used methodologies. Section 4 provides a summary of publications and pointing out CIs w.r.t. appearing fault. Section 5 describes prospects and identifies future research areas. Concluding remarks are drawn in Section 6.

## 2. Brief overview of fixed-axis gearboxes and condition indicators

### *2.1. Gearbox behavior*

All the gears in the gearbox mesh at the same time with their respective pinions which results in sliding of each tooth on other thereby generating vibrations. The line diagram of energy (torque) flow in a fixed axes gearbox consisting two meshing pairs is highlighted in fig 1. The blue vectors shows direction of energy flow from input to output shaft. The following points can be noticed when gears are in operation:

- These gear vibrations are governed by the gear mesh frequency and its harmonics, due to the variable stiffness in the meshing process [10].
- For a pair of damaged meshing gears in fixed-axis gearboxes, fault characteristic frequencies and sidebands emerge symmetrically around the meshing frequency and its harmonics in the frequency spectra [11].
- The signal picked up from accelerometers attached on bearing housing contains several type vibrations from meshing gears, shafts, bearings, etc. The useful characteristics may easily be masked in such strong background noise. Therefore, it becomes difficult to extract fault features of low vibrating nature without denoising [12], [13].

Based on the above points it can be stated that vibration signals are compound in nature. Moreover, if a gearbox with multiple meshing pairs then the fault diagnosis will become more complex.

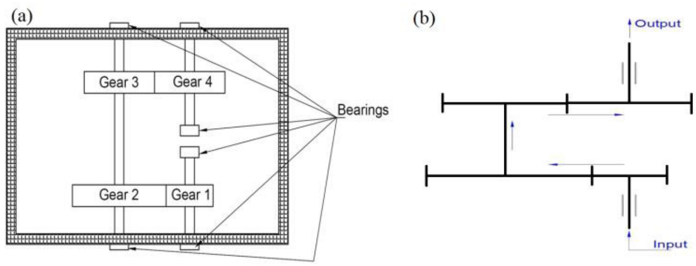


Fig. 1. Torque flow diagram of a fixed axis gearbox having two meshing pairs

### *2.2. Characteristic frequency evaluation*

The distinctive frequencies of a gearbox, comprising gear rotating frequency, meshing frequency and their harmonics are affected by fault. The identification of fault is related to the occurrence of the characteristic frequency which is linked to the given fault. Hence to evaluate the gear mesh frequency of the fixed axis gearbox is important and has been provided here. Let us consider fig1to define the notations,

$Z_i$ – is the number of teeth on gear $i$ $(i = 1,2,3,4)$.

$f_i$ – is the rotating frequency of gear $i$.
The input frequency of whole gear transmission will be same as that rotating frequency of gear1$(f_1)$.
$G_k$ – is the gear ratio of meshing pair $k$ ($k = 1, 2$), which is defined as the ratio of the rotating frequency of the driving gear to that of the driven gear in a meshing pair. Actually, it can also be stated as the ratio of the number of teeth of the driven gear and that of the driving gear, for example, $G_1 = \frac{Z_2}{Z_1}$ and $G_2 = \frac{Z_4}{Z_3}$ ; $f_{mesh_k}$ – is the meshing frequency of meshing pair $k$ ($k = 1, 2$). Therefore, the important frequencies, i.e. the rotating frequencies of each gear and the meshing frequencies of each meshing pair, can be presented as a function of the input frequency $(f_1)$ and the number of teeth of gears as follows.

$$f_2 = \frac{f_1}{G_1} = \frac{Z_1}{Z_2} f_1 \tag{1}$$

In the same way, various frequencies related to different gears can be equated. Expression are mentioned in Table 1

Table 1, Characteristic frequencies of the fixed-axis gearbox

| $f_1$ | $f_2$ | $f_3$ | $f_4$ | $f_{mesh_1}$ | $f_{mesh_2}$ |
|---|---|---|---|---|---|
| Known | $\frac{Z_1}{Z_2} f_1$ | $\frac{Z_1}{Z_2} f_1$ | $\frac{Z_1 Z_3}{Z_2 Z_4} f_1$ | $Z_1 f_1$ | $\frac{Z_1 Z_3}{Z_2} f_1$ |

### *2.3. Condition indicators*

The signals acquired from gearbox via accelerometers are usually in time-domain. Variation in energy appears in signal itself when any fault occurs in a gear. To know the fault appearing phenomenon, CIs are applied, i.e., statistical measurement is conducted of the energy of the vibration signal. Various CIs which are employed are listed below:

(1) R.M.S. - It reflects the vibration amplitude and energy of signal in time domain. The rms is defined as the square root of the average of the sum of the squares of the signal samples [14] and is given by

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

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

(2) Crest Factor- It is defined as the ratio of maximum positive peak value of the signal $x$ to $RMS_x$ [14]and is given by

$$\mathrm{CF} = \frac{\mathrm{x_{0-pk}}}{\mathrm{rms_x}} \tag{3}$$

Where, $pk$ is the sample for the maximum positive peak of the signal and $x_{0-pk}$ is the value of $x$ at $pk$. It is devised to boost the presence of small number of high-amplitude peaks, such as those caused by some types of local tooth damage. It is a unit less quantity and CF of sine wave is 1.414.

(3) Standard Deviation-It measures the amount of variation from the mean value, so it can be calculated as

$$STD = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (x_i - \bar{x})^2} \tag{4}$$

Where, $x_i$ $(i = 1, \dots, N)$ is the $i^{th}$ sample point of the signal $x$, and $\bar{x}$ is the mean of the signal.

(4) Kurtosis- It is the fourth order normalized moment of a given signal $x$ and provides a measure of the peakedness of the signal, i.e. the number and amplitude of peaks present in the signal [14]. It is given by

$$K = \frac{N \sum_{i=1}^{N} (x_i - \bar{x})^4}{\left(\sum_{i=1}^{N} (x_i - \bar{x})^2\right)^2} \tag{5}$$

A signal consisting exclusively of Gaussian distributed noise will have a kurtosis of approximately 3.

(5) Shape Factor- It is used to represent the time series distribution of the signal in the time domain [15].

$$SF = \frac{\sqrt{\frac{1}{N}\left[\sum_{i=1}^{N} (x_i)^2\right]}}{\frac{1}{N} \sum_{i=1}^{N} |x_i|} \tag{6}$$

(6) Energy Ratio- It is defined as the RMS of the difference signal $d$ divided by the RMS of the signal containing only the regular meshing components, $y_d$ and is given by

$$ER = \frac{RMS_d}{RMS_{y_d}} \tag{7}$$

$ER$ is designed to increase in the presence of heavy uniform wear since it would be expected that in this case $RMS_d$ would increase while $RMS_{y_d}$would decrease[16].

(7) Energy Operator (EOP)-An impulse in time averaged vibration signal initiated by damaged gear tooth supported by the energy operator, thus allowing the impulse to be more easily detected [17].

$$EOP = \frac{N \sum_{i=1}^{N} (re_i - \overline{re})^4}{\left(\sum_{i=1}^{N} (re_i - \overline{re})^2\right)^2} \tag{8}$$

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 $x_i$ $(i = 1, \dots, N)$, 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.

(8) Zero Order Figure of Merit (FM0) - It was developed by Stewart in 1977 as a robust indicator of major faults in a gear mesh [18]. Considerable changes in the meshing pattern were found out by comparing the maximum peak-to-peak amplitude of the signal to the sum of the amplitudes of the mesh frequencies and their harmonics. FM0 is given as

$$FM0 = \frac{PP_x}{\sum_{N=0}^{H} P_N} \tag{9}$$

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

(9) Fourth Order Figure of Merit (FM4) - It was developed to accompany $FM0$ by detecting faults isolated to only a finite number of teeth [18]. This is done by first constructing the difference signal, $d$ and then normalized kurtosis of $d$ is then computed as

$$FM4 = \frac{N \sum_{i=1}^{N} (d_i - \bar{d})^4}{\left(\sum_{i=1}^{N} (d_i - \bar{d})^2\right)^2} \tag{10}$$

Where, $\bar{d}$ is the mean of the difference signal.

(10) M6A- It was proposed by Martin in 1989 [18]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

$$M6A = \frac{N^2 \sum_{i=1}^{N} (d_i - \bar{d})^6}{\left(\sum_{i=1}^{N} (d_i - \bar{d})^2\right)^3} \tag{11}$$

(11) M8A- It is developed for being more sensitive than M6A to peaks in the difference signal [18]. It applies the eighth moment normalized by the variance to the fourth power and is given as

$$M8A = \frac{N^2 \sum_{i=1}^{N} (d_i - \bar{d})^8}{\left(\sum_{i=1}^{N} (d_i - \bar{d})^2\right)^4} \tag{12}$$

Notice that increased sensitivity to peaks is not a matter of course of desired property, because a too sensitive parameter may yield many false alarms. Hence, to select the damage indicator is not related specifically to sensitivity.

(12) NA4-It was drawn in 1993 by Zakrajsek, Townsend, and Decker as a general fault indicator which reacts damage and continuing growth of the fault as well [19]. Initially, residual signal $r$ is constructed. The quasi-normalized kurtosis of the residual signal is then 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

$$NA4(M) = \frac{N \sum_{i=1}^{N} (r_{iM} - \bar{r}_M)^4}{\frac{1}{M} \sum_{j=1}^{M} \left(\sum_{i=1}^{N} \left(r_{ij} - \bar{r}_j\right)^2\right)^2} \tag{13}$$

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

(13) NA4*- It was developed to enhance NA4 [20] by Decker et al. in 1994 observing that fault advances from localized to distributed, the variance of the signal becoming larger significantly, causing the kurtosis to retrieve to nominal values after the initial indication of fault. By normalizing the fourth moment by square of average variance from the gearbox under nominal conditions, NA4 is provided with more sensing capabilities. Since it was noticed

that the variance of faulty gearbox signal is greater than that of a healthy gearbox signal, the decision to fix minimum number of data records of a run ensemble is made based on an upper limit, $L$ is given by

$$L = \bar{x} + Z\frac{\sigma}{\sqrt{n}} \tag{14}$$

Where, $\bar{x}$ is the mean value of previous variances, $Z$ is the value for normal distribution, $\sigma$ is the standard deviation of previous variances.

(14) NB4- It was developed in 1994 by Zakrajsek, Handschuh and Decker [21] 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. Similar to NA4, NB4 also uses the quasi-normalized kurtosis. However, alternative to difference signal, NB4 employs the envelope of the signal bandpass filtered about the mesh frequency. The envelope, $s$ is computed using the Hilbert transform and is given by

$$s(t) = \left|\left[b(t) + i[H(b(t))]\right]\right| \tag{15}$$

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

(15) Delta RMS- This parameter is the difference between two consecutive RMS values [22]. This parameter focuses on the pattern of vibration and is sensitive to vibration signal changes.

(16) Sideband level factor-The sideband level factor [26] is defined as the ratio of sum of the first order sideband about the fundamental gear mesh frequency to the standard deviation of the time signal average.

$$SLF = \frac{\sum_{i=1}^{n} si_{gearmesh\pm i}}{S_{std}} \tag{16}$$

Where, $si$ is the amplitude of the $i^{th}$ sideband around fundamental gear meshing frequency, $S_{std}$ is the standard deviation of the time signal average. For a gearbox in healthy condition this factor is near zero.

(17) Sideband index- The sideband index [23] is defined as the mean amplitude of the sidebands of the fundamental gear mesh frequency.

$$M = \frac{1}{k}\sum_{i=1}^{k} S_{max\ \ i} \tag{17}$$

Where, $M$ is sideband index, $k$ is the number of sidebands and $S_{max\ \ i}$ is the $i^{th}$ maximum linear amplitude of sideband. It is a way to measure sidebands in spectrum for pinion quality for commissioning of gears.

(18) CAL4- It is developed by Samuel and Pines in 2009, uses the prediction error between a model generated from healthy gears and the input taken from current gears as a metric to find out fault [24]. The metric is quantified using a normalized kurtosis of the prediction error vector for the whole gear

$$CAL4 = \frac{N\sum_{i=1}^{N}(x_i-\bar{x})^4}{\left[\sum_{i=1}^{N}(x_i-\bar{x})^2\right]^2} \tag{18}$$

Where, $\bar{x}$ is the mean of $x$ and $N$ is the total number of the data points in $x$.

(19) Clearance factor[25]

$$Clearence\ Factor = \frac{max(|x_i|)}{\left(\frac{1}{N}\sum_{i=1}^{N}\sqrt{|x_i|}\right)^2} \tag{19}$$

(20) Impulse indicator[25]

$$Impulse\ indicator = \frac{max(|x_i|)}{\frac{1}{N}\sum_{i=1}^{N}|x_i|} \tag{20}$$

(21) Correlated Kurtosis- It takes benefit of the periodicity of the damage and is used to identify periodic impulses due to faulted gear tooth. Correlated kurtosis of M-shift for measured data set $x$ [26] is defined as

$$CK_M(T) = \frac{\sum_{n=1}^{N}\left(\sum_{m=0}^{M} x_{n-mT}\right)^2}{\left(\sum_{n=1}^{N} x_n^2\right)^{M+1}} \tag{21}$$

Where, T is the period of interest (the period for fault signature that needs to be detected).

(22) Mean frequency- It is a frequency domain parameter, extracted from the frequency spectrum of the gear vibration signal [[27]].

$$MF = \frac{1}{N}\sum_{n=1}^{N} X_n \tag{22}$$

Where, $X_n$ is the $n^{th}$ measurement of the frequency spectrum of signal $x$ and $N$ is the total number of spectrum lines. MF indicates the vibration energy in the frequency domain.

(23) Frequency center (FC)[27]

$$FC = \frac{\sum_{n=1}^{N} f_n X_n}{\sum_{n=1}^{N} X_n} \tag{23}$$

Where, $f_n$ is the frequency value of the $n^{th}$ spectrum line. FC shows the position changes of the main frequencies.

(24) Root mean square frequency(RMSF) [27]

$$RMSF = \sqrt{\frac{\sum_{n=1}^{N} f_n^2 X_n}{\sum_{n=1}^{N} X_n}} \tag{24}$$

(25) Standard deviation frequency(STDF) [27]

$$STDF = \sqrt{\frac{\sum_{n=1}^{N} (f_n - FC)^2 X_k}{\sum_{n=1}^{N} X_n}} \tag{25}$$

(26) Spectral Kurtosis- The spectral kurtosis (SK) is a statistical tool which indicates the presence of sequences of transients and their locations in the frequency domain [28], [29] and is evaluated below

$$K_Y(f) = \frac{K_X(f)}{[1+\rho(f)]^2} \tag{26}$$

Where, $K_X(f) > 0$ is the SK of signal and $\rho(f)$ is the noise-to-signal ratio i.e. $\rho(f) = S_N(f)/S_X(f)$ with $S_N(f)$ and $S_X(f)$ the power spectral densities of the noise and faulty gear signal.

(27) Shannon Entropy- It is a statistical indicator used in time-frequency domain analysis to describe the distribution of energy of wavelet coefficients of the gear vibration signal. The uncertainty of signal wavelet coefficients is measured by Shannon entropy[30] which is defined by

$$H_e = -\sum_{j=1}^{J} p_j \log p_j \tag{27}$$

Where, $p_j = E_j/E$ is the percentage of energy of the $j^{th}$ frequency band signal of WPT, where $E = \sum_{j=1}^{J} E_j$.

(28) Fourth Order Normalized Power (NP4)-The normalized kurtosis, a fourth order statistical parameter calculated for instantaneous power distribution, provides the gear-fault-detection parameter [31].

$$\mathrm{NP4} = \frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{N}} \left(\frac{\mathrm{P}(\mathrm{t_i} - \bar{\mathrm{P}})}{\sigma}\right)^4 - 3 \tag{28}$$

Where, $\sigma$ is the standard deviation of $P(t)$.

## 3. Review of CIs for gear fault diagnosis

In general, a gearbox vibration signature consists of three important components: a sinusoidal component w.r.t time, periodic transients due to defect and random noise. As fault occur and propagates through the system, the sinusoidal components show both modulation and variation in amplitude [32]. To identify the cause of variation in vibration signal, CIs are being applied. Appearing challenges in fault diagnosis of gearboxes, researchers have carried out numerous investigations resulting journals, conference proceedings and technical reports citing CIs. Specifically in recent years, publications on CIs have been prioritized and have been reviewed below.

### *3.1. Time domain indicators*

CIs are commonly used to administer severity of the vibrations for some fault modes, like pitting, crack and wear on the components like gears in gearboxes in mechanical fault detection [33]-[38]. This section is intended to describe these studies which are as follows. Bechhoefer et al. [39] concluded as the CIs for AE enveloped signal were 3x more significant than for the vibration. Zakrajsek et al. [40] deployed all time domain statistical indicators individually on the thin rim spur gear and concluded that these techniques were unable to give early information of the fatigue crack prior to rim fracture. Again in 1994 Zakrajsek [41] reviewed that no one method detects tooth spall, scoring, wear, crack, pitting. FM4, NA4*, NB4* exhibits more fault detection capability comparatively, for 120 hours of run. Dempsey and Zakrajsek [42]conducted research to reduce the effect of load on the vibration-diagnostic parameter NA4. Both NA4 and FM4 demonstrate that, when destructive pitting occurs on one gear tooth. Zakrajsek et al. [43] concluded thatFM0 indicate only the moderate variation as the damage initiates and advances. NA4* provides the more strong evidence as the pitting progresses. It is very delicate to speed variations. In the scenario of multi component fault expectation, FM0 is found to be ineffective. Parey and Tandon [47] and [48] evaluated kurtosis value from the selected IMFs for incipient fault detection of gearbox. Wang [49] calculated kurtosis and envelop kurtosis and observed that envelop kurtosis provides a better indication of fault. Ma et al. [50] reported that for measured signals sideband frequencies, statistical features (rms and kurtosis) are sensitive to fault features of the cracked gear coupled rotor system. The Sideband Index (SI) and Sideband Level Factors (SLF) were consistently positive in identifying the existence of a fault in test cell conditions [51]-[53], whereas no other features were able to detect a crack at the low torque levels tested. Hong and Dhupia [54] combined the fast dynamic time warping and the correlated kurtosis (CK) techniques to characterize gear local fault for both fixed as well as planetary gearboxes.

### *3.2. Frequency domain indicators*

Antoni [55] stated about the kurtogram as a powerful analysis tool of non-stationary signals, to detect transients buried in strong background noise opened up many new perspectives. Combet and Gelman [56] applied the technique for diagnosis of local faults in gears. Their approach is associated with time synchronous averaging. Barszcz and Randall [57] showed that there are cases of gear damage, where the TSA will not give results, because of too much frequency span, in such cases SK provided good results, diagnosing fault several weeks prior in comparison to other methods. Loutas et al. [58] compared the performance of mean frequency (p12), standard deviation frequency (p17). Liu et al. [59] proposed an adaptive SK filtering method on the grounds of Morlet wavelet.

### *3.3. Time-frequency domain indicators*

Yu et al. [60] presented the diagnosis approach of Shannon entropy based on Hilbert transform that could identify gear status-with or without fault accurately and efficiently. Lei et al. [61] experimented several fault features including Shannon entropy to reveal gear health conditions. On the basis of appropriate decomposition level and Energy-to-Shannon entropy ratio for selecting optimal wavelet, Zhang, et al. [62] investigated length of time window to suppress noise effects and ensure appropriate time resolution. Yan and Gao [63] studied maximum energy-to-shannon entropy ratio standard for quantitatively analyzing performance of five complex-valued wavelet functions in fault diagnosis. Polyshchuk et al. [64] initially compared the kurtosis value to NP4 parameter for basic signal which demonstrated the potential of NP4 to indicate single gear tooth damage successfully. Also, NP4 decays as the severity of the fault increases on the multiple gear teeth. Combining time domain CIs with Wigner- Ville Distribution produces better fault diagnosis results [65]. Choy et al. [66] studied the behavior of vibrations in a gearbox for surface pitting, wear, and partial tooth fracture of the gear teeth using time frequency technique associated with time domain parameters.

## 4. Performance assessment of CIs

A number of wear mechanisms such as abrasive wear, pitting, micro-pitting, chipping, scuffing, spalling, crack, breakage and white structure flaking are found to initiate majority of the gearbox failures [67]-[69].

Table 2, Condition monitoring indicators of time domain and respective fault

| **Condition Indicators** | **Fault** | **References** |
|---|---|---|
| RMS, Delta RMS | General fault progression | [14][22][39][44][46][50] |
| Kurtosis | Breakage, wear | [14][39][46][49] |
| Crest factor | Impulsive vibration due to tooth break | [14][39] |
| Energy ratio | Heavy Wear (more than one tooth on a gear) | [16] |
| Energy operator | Scuffing, severe pitting | [17][40] |
| FM0, FM4 | Wear/ scuffing/ pitting and tooth bending due to root crack | [14][18][44][45] |
| NA4 | Progressive damage(localized to distributed transformation) | [19][40][42][44] |
| SLF | Misalignment | [22][51][53] |
| SI | Pinion quality indicator | [23][51][53] |
| M6A, M8A | Surface damage indicators | [18] |
| NB4 | Localized fault | [21][40] |

To offer a timesaving approach, all the studies of CIs in the literature reported by researchers are compiled with all references into Table 2. Significant progress is made in fault diagnosis on the basis of CI applied to gearboxes of helicopter, rolling mill or of wind turbine. Yet, some important problems still left unsolved in reported studies. They are pointed out as follows

- The indicators reported in literature were recognized on the basis of many assumptions. Hence, they failed to show accurately the fault characteristics. In addition, most indicators were devoted to investigate fatigue crack fault gears, while few concentrated on the studies of pitting ones.
- Many established CI for gearboxes were geared to stationary speed operations. But, if variation of speed and load is considered, there may be a change in the performance of CI, which is not mentioned yet.
- A gearbox is a mechanism of gear, shaft, bearing and case, so the whole combination will degrade from gears to shaft and shaft to bearing, researchers have treated elements of gearboxes, like bearings, gears and shafts separately, which is not appropriate method of conducting research, because, it isn't the real time degradation or fault appearing phenomenon.
- No single method is capable of predicting fault consistently even for long run of observation. For example, NA4* and NB4* are responsive against early pitting; however they fails against tooth fracture. So, it needs to be associated with other methods like WVD for and FM0-FM4 simultaneously for pitting.

## 5. Prospects

Despite of all, researchers have introduced some CI for fault detection and its continuation for gearboxes still following prospects can be considered as future research possibilities in the realm of CI for condition monitoring.

- In a gearbox, gear meshes and produces vibration. Along with this bearing and shaft also generates vibration which may be in different phase. These vibrations may mask the gear vibration which may neutralize or weak them. Therefore, an unmasking approach to segregate multi-mode vibrations for multimode damage is one of the issues that should be taken care of.
- Considering the effect of varying load and fluctuating speed, there is a need to develop CI which can detect the fault at initial stage or progressing crack. Need to utilize the capturing of momentary impulses produced from gears at the initial stage of damage. However, kurtosis or spectral kurtosis provides the overall health of gearbox but doesn’t give detail information about specific fault that is appearing.
- To identify gearbox damage, transducers (accelerometers) are basically sticked on the housing of gearboxes to acquire vibration signal. Since, gears mesh with each other and shaft rotates accordingly, there are time variant vibration transmission paths from gear to the attached transducers. Therefore, further modulating components also appear into the measured vibrations. Now it’s a challenging issue to distinct and extracts the modulating components of faults from those caused by time-varying transmission paths which are overlapped.
- Many researchers illustrated the usefulness of their techniques utilizing their own typical readings whether for helicopter or rolling mills, but for any other data whether, these methods will still work well or not there is no such surety of that. Thus, performing more investigations with different and mixed fault modes and severities, to supplement the database and forming the standards that are important to test the strength of new diagnosis indicators.

## 6. Conclusion

Summing up the review on statistical indicator for gear fault diagnosis, over the past two decades, much time for research has been devoted to the development of CI based fault diagnosis techniques. Many of these indicators were illustrated for fault identification in condition monitoring and fault diagnosis of gearboxes. Literature is surveyed and categories under different headings. Finally, some issues in this area of research are outlined and provision for improvement and thus research into new damage detection techniques is continuing.

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