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Review Article

A Review on Different Faults in Gearbox and Vibration Based Diagnosis

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Abstract

The present work lists a summary of different faults in the gearbox and vibration-based diagnosis techniques to identify them. The gear is used in different loads, and environmental conditions are prone to degradation. The different failures and their detection techniques. These techniques are helpful for the early detection and timely remedial of faults. Current work listed the vibration-based techniques of fault detection.

Keywords: *Faults, diagnosis*

1. Introduction

In today's time, the complex system brings more interdependence among the system elements (bearings, gears, cam, shaft etc.). The failure of one brings the whole system to shut down—the gearbox is prone to failure due to excessive load and environmental conditions. Gearbox failures are divided into lubricated (pitting, mild wear etc.) and non-lubricated failures (fracture, bending etc.)[1]. In literature the failure of bearing[2–53], lubrication[2,5,36,47,50–52,54,55] and gears are listed[38,56,65–74,57,75–77,58–64]. The gearbox operates under both constant and varying operating conditions. The gearbox consists of gears, shafts, bearings and support structures. Under the varying operating condition, the gears continue to degrade. If the gear faults are not detected early, this may be the reason for the substantial monetary and life losses [78]. In the gears, the stresses are pure rolling at the pitch line; above and below the pitch line, rolling-sliding action takes place; the sliding is in the opposite direction [1,79–82]. The sliding interfaces have no problem if appropriately lubricated. In insufficient lubrication, surface disparities are in direct contact and differential surface hardness, rise in temperature, and adhesive bonding under high pressure contribute to the breakdown of the gear surfaces[1,81]. The gear's roots have tension (loaded side) and compression (opposite side) simultaneously. The root is the point of highest stress in tension. The bending strength of the root is the direct function of the surface hardness, surface smoothness, sharpness of radius and the fault (crack/ pitting etc.)[1,83]. Under these conditions, the gear material is under continuous degradation and when the failure crosses the threshold called failure.

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The gear failures are classified based on lubrication and non-lubrication. The gear pairs work under the elastohydrodynamic lubrication and partial-elastohydrodynamic lubrication mechanism. The non-lubricated failures include the overload and bending types of failure. The lubricated failure is a set of fatigue (pitting), wear, and scuffing. The gear teeth, due to deterioration, generate dynamic forces which accelerate the gear tooth failure. Lubricant properties are determinantal for the safe working of the interfaces in contact. The wear is a continuous process when two surfaces are in contact, and the threshold depends upon the expected lifetime.[1]

Every machine element exhibits a unique vibration signature under standard conditions. The faults change the signature in how it is related to the fault. If a machine does not have any fault, it generates vibrations; these vibrations relate to the periodic events of machine operation. These consists of harmonics of the rotating shaft, meshing of gear teeth, electric field etc. These harmonics are a reliable indicator of the sources and can be used as a diagnostic tool[84,85]. The vibration from different sources consists of different information; to quantify the source, it is necessary to understand the behaviour of the vibration output of the different sources. The vibration analysis consists of studies such as time, frequency, and time-frequency domains [86–88]. All studies give different types of fault information. Most of the gearbox vibration analysis studies are focused on the gear mesh harmonics and the sidebands. The change in the gear mesh harmonics amplitude and the number of sidebands indicate the type of failure like if the sidebands are increasing and the gear mesh harmonic keeps constant, pitting in gear is dominating. If the higher gear mesh harmonics are coming into the picture, the gear is going through mild-wear. So, the harmonics analysis accurately represents which type of fault exists.

The present study summarizes the different failure and vibration-based techniques for diagnosing the faults.

2. Types of failure in the gearbox

All Gears are the toothed wheel used to transmit the power and motion by the active engagement of the teeth. Due to dynamic operating conditions, gear is prone to deterioration/ failure and an increase in noise and vibration level of the system. The American Gear Manufacturing Association (AGMA) has classified these deterioration/ failures under the five broad categories: wear, scuffing, deformation, contact fatigue, cracking and bending [89,90]. These faults can be further classified under two broad categories: lubrication-related and non-lubrication-related failures. The non-lubrication-related failures include failures resulting from overloading and fatigue due to bending. Lubrication failures include wear, scuffing/ scoring, and Hertzian fatigue (Pitting/ micro-pitting) [90,91].

2.1 Non-lubrication-related failures

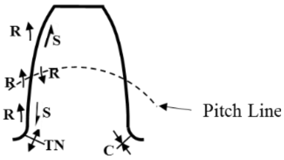
2.1.1 Plastic flow

Plastic flow results from plastic yielding of the surfaces having relative motion, usually associated with the high load and high temperatures. A band of bright finish develops along the pitch line due to the reversal of direction of sliding at the pitch line. The material's plastic flow on the driver's teeth and driven gear are associated with the direction of the friction forces. In driven gear, it is towards the pitch line; in driving gear, it is away from the pitch line. The low viscosity of the lubricant and the lack of surface hardness are the main reason behind the plastic flow[89,90]. The local elastic deformation of the gear surfaces gives rise to elastohydrodynamic lubrication.

2.1.2 Tooth fracture

Tooth fracture is the breaking of the teeth into pieces. The fracture occurs due to high load (impact or static) and cyclic fatigue (high cycle or low cycle) of the gear material. Bending fatigue failure occurs over a long period [89,90,92–95]. It starts with the initiation of crack at the weakest point, mainly at the root of the tooth or at the fillet where high-stress concentration exists, along with the highest tensile stress from bending or from the defects[96–98]—fast crack propagation results in fracture of the gear tooth. The tooth breakage results from the load concentration along the tooth flank length due to the errors in machining and assembly or large elastic deformation of the shafts; tooth wear leads to the weakening resulting in increased dynamic loads. Cracks formed at the root, and the fibres are under tension or along the maximum principal stress direction on the tensile side of the gear tooth[99].

Path of crack propagation paths and their dependencies on the rim and web thickness, initial crack location, and backup ratio (ratio of rim thickness and tooth height) have been discussed in the literature [93,100,101]. Many researchers concluded that gear cracks propagation paths are continuous, smooth and, in most cases, straight with slight curvature [1,93,102].



R: Rolling stress
S: Shear stress
TN: Tensile stress
C: Compressive stress

Fig.1 Stress areas on the spur gear tooth [1]

2.2 Lubrication-related failure

2.2.1 Hertzian fatigue (Pitting and micro pitting)

Pitting is the most common mode of failure in gear teeth. The teeth of the gear are subjected to high Hertzian contact stresses due to non-conformal contacts. The surface starts to deteriorate as they continuously pass under many stress cycles. Pitting is a function of the surface hardness, the load cycles, duration of the operation, and lubricant properties[59,89,94,103–111]. Pitting results from fatigue crack; it initiates either on the surface or the small depth below the surface. The crack paths are branched and, on reaching the surface, separate a piece of the surface-material forming pit[112,113]. The pitting may occur even at low stresses because there is no endurance limit for the Hertzian stresses. The gear design can be optimized to increase the pitting resistance[105,112–114]. This is a surface phenomenon and takes time to develop. The presence of oil film modulates the intensity of stresses on the surface but does not eliminates it [90]. The motion in the gear pair is pure rolling at the pitch line; the pits are of small size and non-progressive. The oil is incompressible and will not cushion the pressure exerted in pure rolling. The area above and below the pitch line is more prone to pitting because sliding plays an important role.

Fig.2 Pitting stages of the pinion for health assessment [115]

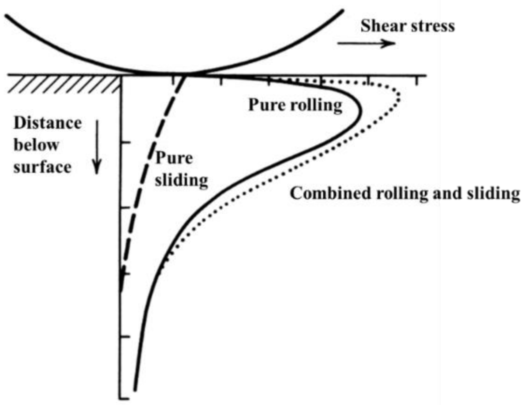


Fig.3 Stress distribution in contacting surfaces due to rolling, sliding and combined effect [1,107]

2.2.2 Wear (mild wear/rubbing wear)

The progressive loss of material between interacting surfaces is called wear. Wear is a function of load, velocity, material hardness, and lubricant properties. When the lubricant film is not sufficient to avoid contact between the interface surfaces, it leads to the removal of material from the interacting surfaces[116]. One form of wear is adhesive wear; the metal transfer causes that due to localized welding of asperities. Adhesive wear is usually considered classified as a mild form of wear. The other form is abrasive wear, caused by abrasive action between the relatively moving surfaces and the presence of the abrasive particle (local and foreign) between them. The ASM handbook defines "the mild-wear when the gearset is prone to wear instigated by adhesion, abrasion, and polishing and only confined to the oxide layers of the gear tooth surface. When oxide layers breakdown brings, the surfaces are in direct metal-to-metal contact. Also, transition to severe adhesive wear usually occurs". The lubrication mechanism plays an essential role in determining the factors like friction regime, and the factors which determine failures are less noticeable. The shape of wear particles tells about the existing wear mechanism and the severity of the wear. The modest wear amount depends upon the expected lifetime for gears. When the thickness of the gear reduces to the extent that bending fatigue is possible[117], high dynamic loads occur. The lubricant viscosity affects the wear rate significantly.

2.2.3 Scuffing or scoring

Scuffing is a severe form of adhesive wear caused due to increase in temperature due to lubrication failure. The lubrication failure allows the metal-to-metal contact at the flank surface; the condition of the load and temperature cause welding at asperities and tears apart as the surfaces are in motion[89,96,106]. Scuffing is the function of the total contact temperature [1,90]. The surface is characterised by marking in the direction of sliding. The scuffing surfaces are characterised as rough, matte, and torn surfaces. Gears teeth operated under boundary conditions face scuffing failure. [1]

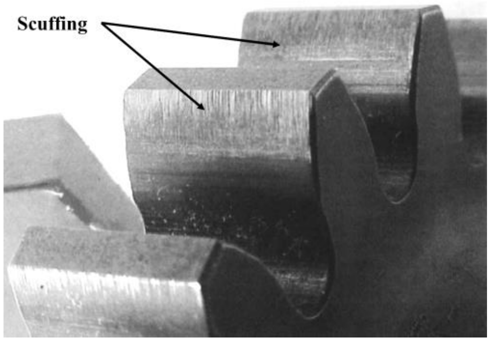


Fig. 4 Specimen gear with scuffing failure [1,91]

3. Vibration-based diagnosis of the gearbox

The gearbox degrades over time, and it becomes essential to find the severity of the degradation. All the faults are interrelated in either one or another form. Too often, it is also impossible to open the system to inspect the gearbox visually. So, non-destructive techniques are applied to get information about the system's current state. A database is created to get the change in the system's state by collecting the different types of data from the gearbox. The data collected is categorized into two main types: event and condition monitoring data. The event data provide information about what happened (installation, overhaul etc.) and what was done (repair, oil change, etc.). In condition monitoring, data is related to the health condition of the system.

The data related to the system is susceptible to environmental conditions; it includes vibration data, acoustic data, oil analysis data, temperature, wear data etc.

3.1 Vibration data analysis

Vibration is the "motion of a machine, machine part, back and forth from its mean position of rest". Every machine/ component has a unique vibration signature. As the degradation occurs, the vibration signature changes. The mechanical faults related to the machinery operation which cause vibrations are imbalance, eccentric components, misalignment, bent shaft, component looseness, damaged gear, resonance, rubbing etc. These faults cause the forces to change either in magnitude or in direction. Each cause of vibration owns individual vibration characteristics — the collected vibration data is processed through numerous signal processing techniques and algorithms in literature for diagnostics. There are three main categories of data analysis: time-domain analysis, frequency-domain analysis and time-frequency analysis[118].

Table 1 The vibration-based statistical parameters

	Statistical Parameter	Formula	References
1	RMS	$\sqrt{\frac{1}{N}\left[\sum_{k=1}^{N}(y_k)^2\right]}$	[118–125]
2	Peak Value	$y_{max}(t)$	[125]
3	Crest Factor	$\frac{y_{pk-pk}}{y_{rms}}$	[118–120,126]
4	Kurtosis	$\frac{N\sum_{k=1}^{N}(y_k-\bar{y})^4}{\left[\sum_{k=1}^{N}(y_k-\bar{y})^2\right]^2}$	[56,118–122,126–129]
5	Shape Factor	$\frac{\sqrt{\frac{1}{N}\left[\sum_{k=1}^{N}(y_k)^2\right]}}{\frac{1}{N}\sum_{k=1}^{N}\lvert y_k\rvert}$	[118]
6	Energy Ratio	$\frac{y_{rms}(d)}{y_{rms}(r)}$	[118,120]
7	Energy Operator	$\frac{N^2\sum_{k=1}^{N}(\Delta x_k-\Delta\bar{x})^4}{\left[\sum_{k=1}^{N}(\Delta x_k-\Delta\bar{x})^2\right]^2}$ $\Delta x_k = y_{k+1}^2 - y_k^2$	[118,120]
8	FM0	$\frac{y_{peak-peak}}{\sum_{k=1}^{N}A_k}$	[118,120,121,130]
9	FM4	$\frac{N\sum_{k=1}^{N}(d_k-\bar{d})^4}{\left[\sum_{k=1}^{N}(d_k-\bar{d})^2\right]^2}$	[99,118,120,122,128,130,131]
10	M6A	$\frac{N^2\sum_{k=1}^{N}(d_k-\bar{d})^6}{\left[\sum_{k=1}^{N}(d_k-\bar{d})^2\right]^3}$	[99,118,120]
11	M8A	$\frac{N^3\sum_{k=1}^{N}(d_k-\bar{d})^8}{\left[\sum_{k=1}^{N}(d_k-\bar{d})^2\right]^4}$	[99,118,131]
12	NA4	$\frac{N\sum_{k=1}^{N}(r_{kj}-\bar{r}_j)^4}{\left[\frac{1}{j}\sum_{j=1}^{j}\left\{\sum_{k=1}^{N}(r_{kj}-\bar{r}_j)^2\right\}\right]^2}$	[99,118,120–122,128,130]
13	NB4	$\frac{N\sum_{k=1}^{N}(E_k-\bar{E})^4}{\left[\frac{1}{j}\sum_{j=1}^{j}\left\{\sum_{k=1}^{N}(E_{kj}-\bar{E}_j)^2\right\}\right]^2}$	[118,120]
14	Sideband Level Factor	$\frac{\sum_{k=1}^{N}sk_{gearmesh\pm k}}{S_{std}}$	[118,123,132]
15	Sideband Index	$\frac{1}{N}\sum_{k=1}^{N}s_{max\,k}$	[118]
16	CAL4	$\frac{N\sum_{k=1}^{N}(y_k-\bar{y})^4}{\left[\sum_{k=1}^{N}(y_k-y)^2\right]^2}$	[118]
17	Clearance Factor	$\frac{max(\lvert y_k\rvert)}{\left[\frac{1}{N}\sum_{k=1}^{N}(\sqrt{\lvert y_k\rvert})\right]^2}$	[118]
18	Impulse Indicator	$\frac{max(\lvert y_k\rvert)}{\frac{1}{N}\sum_{k=1}^{N}(\sqrt{\lvert y_k\rvert})}$	[118]
19	Shannon Entropy	$-\sum_{\alpha=1}^{n}p_\alpha\log p_\alpha$	[118]
20	NP4	$\frac{1}{N}\sum_{k=1}^{N}\left(\frac{P(t_k-\bar{P})}{SD}\right)^4-3$	[118,121]
21	CCR	$\frac{\sum_{i=1}^{N}(RH_i-\overline{RH})(R_i-\bar{R})}{\sqrt{\sum_{i=1}^{N}(RH_i-\overline{RH})^2}\sqrt{\sum_{i=1}^{N}(R_i-\bar{R})^2}}$	[115]

In time-domain analysis, the time waveform is directly processed. The waveform analysis calculates characteristic features from time waveform signals as statistic parameters such as RMS, peak value, kurtosis, crest factor, shape factor, energy ratio, NA4, FM4, CCR etc. These parameters are briefed in Table 1. The waveform signal is processed through time synchronous average (TSA) before calculating the statistical parameters. The autoregressive (AR) filter is used to remove the dominating gear mesh harmonics from the signal[96]. The regression process develops some parameters, and the regression techniques are linear regression and non-linear regression[133]. The TSA is used to average the raw signal over a number of revolutions to remove or reduce the noise and the effects from other sources [120,134–136]. The time-domain averaging across all scales (TDAS) represents the frequency domain wavelet transformation and synchronous averaging of signals. TDAS is the geometric average that ensures the periodic impulses due to fault and multiplication of the faults in magnitude due to increased fault and fault transfer from one tooth to another [136].

The frequency-domain analysis is based on transforming the time signal into the frequency domain. It provides flexibility to identify and isolate specific frequency components of interest. The complex time-domain signal is divided into a number of frequency pockets. It is easy to focus on the frequencies of interest. The Fast Fourier Transform (FFT) is the most common technique to discretise the time-domain signal into different frequency components[82,137]. The relative vibration levels at different frequency bands can provide some diagnostic information. MF, frequency centre, RMSF, and STDF are the few frequency-based vibration indicators used for condition monitoring. The sidebands about the gear mesh frequency component are due to amplitude modulation, and frequency modulation of the vibration signal provides valuable information[138,139]. The gear system has a large number of frequency components due to the complexity of the system. Cepstrum is the inverse of the Fourier Transform of the logarithmic power spectrum [82,134,135,137,140]. It can detect the harmonics and sideband pattern of non-Gaussian signals. It helps separate forcing functions from the transfer functions to various measurement points. The machine operating with constant rotational speed undergoes a drift in the operating speed over time, which also cause the variation in vibration frequencies. To overcome this, synchronous resampling of the signal can be done, and the sampling rate of analyses is linked to the speed of the machine. Spectral Kurtosis (SK) is explicitly defined as the kurtosis of the frequency component compared to the variability in the amplitude of different spectral frequencies[82,129]. The technique was based on Short Time Fourier Transform (STFT) [82,135]and has given a measure to the impulsiveness of the signal as a function of frequency. SK can be used as a filter by its nature of working because it is significant in frequency bands where the impulsive faults are dominant and effectively zero where the stationary components dominate the spectrum.

The joint time-frequency analysis can overcome the inability to handle non-stationarity in the signals common to most machinery faults. The non-stationarity is time and angle dependent[141]. Time-frequency analysis provides information on the evolution of the signal's spectral content along with time. Short-Time Fourier Transform (STFT) is a windowing technique applied to Fourier Transform[142,143]. The window may be finite such as Hanning, or theoretically infinite such as Gaussian. The STFT formulation is defined as[82,135,144]:

$$S(f,\tau) = \int_{-\infty}^{\infty} x(t)w(t-\tau)e^{-j(2\pi ft)}dt \quad (1)$$

Where; w(t) is a window moving along the record.

Winger-Ville Distribution (WVD)[130,143,145] is a bilinear transform in which time and frequency functions are linked together in one function, giving better time localisation. WVD limitation is the interference of other components' frequency elements between the actual component's frequencies. WVD possesses a joint function for the time and frequency distribution, enabling a signal's energy density or intensity to be described simultaneously in time and frequency. WVD is defined as[146,147]:

$$W_x(t,f) = \int_{-\infty}^{+\infty} x^*(t-\tau/2)x(t+\tau/2)e^{-i(2\pi f\tau)}d\tau \quad (2)$$

Where; Wx(t,f) denote the WVD of the signal. x* is the complex conjugate.

Wavelet Transform (WTs)[134,140,143,145,147–151] compares several components of the vibration signal at different resolutions, which is not available with the STFT, where the local frequency content of the signal is measured. In WTs, the window is oscillating and is called a mother wavelet. The WTs signal is decomposed into basic functions called wavelets. The decomposition of the signal into time-frequency space provides the possibility to determine the existing frequencies and the duration of each frequency in time. The wavelet transform is defined as [82,87,92,135,136,152,153]

$$W(a;b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} x(t)\,\psi^*(\frac{(t-b)}{a})dt \quad (3)$$

Where; x(t) is the waveform signal, a is the scale parameter, b is the time parameter, and ψ(.) is a wavelet, which is a zero-average oscillatory function centred around zero with finite energy, and “*” denotes complex conjugate. The mainly used wavelets are continuous wavelet, Morlet, Haar, Hermitian etc. [154,155].

The other techniques apart from the time domain, frequency domain, and time-frequency domain analysis to reduce the noise in the signal and extract some information are Time synchronous averaging (TSA), order analysis, Independent component analysis (ICA), Bounded component analysis (BCA), Principal component analysis (PCA), Empirical mode decomposition (EMD).

Time Synchronous Averaging (TSA) allows the removal of a non-stationary component of noise from the vibration signal. The basics of TSA is that all vibration related to gears on the shaft will repeat periodically with shaft rotation. By dividing the vibration signal into segments with each having the same length as the shaft period and ensemble averaging a sufficiently large number of segments, the vibration, which is periodic with shaft rotation, will be enhanced. TSA of the vibration can help eliminate all frequencies except the fundamental and harmonics of the tooth meshing frequency from the gear vibration signal[120,128,134–136,142,156].

Order analysis provides the flexibility of analysing the signal with changing rotational speed. Most machine operates under changing rotational speeds[136]. The change in the speed causes the change in the position of frequency components in the spectrum and causes spectrum smearing. The order analysis is typically accomplished using a reference signal coupled to the rotating shaft. The order analysis provides the sampling of the signals at the same angle, and the frequency content of the signal will be a function of the order[149,157–159].

Most signals contain noise. To extract the exact information from the signal, separating this noise from the signal is required. The Independent Component Analysis (ICA) [160]provides this analysis flexibility by providing the function to make different component signals independent of each other. If two component signals are independent of each other, then the characteristics of one do not affect the characteristics of the other signal[149]. In the case of the gearbox signal, the independence between the harmonic characterisation of the gear and the impulsive characterisation of the bearing is considered. So, different characteristic faults can be captured.

In the case of coupled faults, it becomes essential that the source characteristics should be known, like forces and geometrical properties. The Bounded Component Analysis (BCA)[149] provides the flexibility of separating the independent and dependent signal sources for analysis. In BCA, the compactness, non-degradency and Cartesian decomposition of the support source are assumed. In the gear system, this is used to decouple the gear and bearing faults for locating the primary fault source.

Principal Component Analysis (PCA) is a multivariate technique that analyses the complete data with several inter-correlated quantitative dependent variables. It extracts and expresses this information as a set of orthogonal variables called principal components. PCA transforms the two features into uncorrelated ones by keeping the features' uniqueness [161].

Empirical Mode Decomposition (EMD) can decompose a signal into several intrinsic mode functions (IMFs)[126,149,162,163]. The hybrid faults can be detected by applying Hilbert demodulation on the IMFs. The underlying assumption is that: the signal has at least two extrema, one maximum and one minimum, the time lapse between the extrema defines the time scale, and if data is devoid of extrema but contains only an inflexion point, then it can be differentiated to revel the extrema. Hilbert-Huang is to decompose the complicated and non-stationary signal into finite number of IMFs[130,140,147,153,163,164].

Table 2 Frequency component and probable cause

Frequency component	Cause (Most likely)	Citation
1X (Rotational Harmonic)	Imbalance, manufacturing error	[82,164–166]
2X (Rotational Harmonic)	Mechanical looseness, Misalignment	[82]
3X (Rotational Harmonic)	Misalignment, crack	[82,166,167]
Sub- Harmonics	Deformation of contacting surfaces	[168]
Synchronous (ac line frequency)	Electrical	[159]
Gear Mesh	Healthy, Profile modification (Backlash, clearances)	[159,165]
Frequency Sidebands	Pitting severity, broken/missing tooth	[146,153,169]
Higher Harmonics (Gear mesh)	Wear (mild-wear, clearance)	[106,137,170–172]
Increasing Gear Mesh Harmonic	Eccentricity (mounting)	[167,173]

Conclusions

The paper mainly reviewed the different types of faults and their developing mechanisms, statistical parameters for vibration-based techniques for diagnosis, and processing techniques of vibration data. The following suggestions are inferred for future research prospects:

a. A proper fusion technique combines the effect of the vibration and the tribological aspects for the early detection of the failure.
b. Most parameters are defined for a single type of fault at a time in the gear system. The existence of local and global hybrid faults deserves some investigation. The literature [149] talks about the global hybrid fault investigation techniques. But, local hybrid faults deserve investigation.

c. The technique to separate the masking effect of bearing and shaft vibration signals. The wavelet and the EMD are trying to rectify this problem but still need to improve the matching efficacy of the wavelet and the solution to the mode mixing.

d. . The fluctuation in the speed makes the modulation dominate. Hence, A parameter that can recognize the fluctuating speed and load effects at the early stage of the fault must be defined.

Nomenclature

t	Time
T	Non-dimensional time
N	Number of data point
$y_{max}(t)$	Time-domain vibration signal
y_k	kth sample point of signal
y_{rms} and $y_{rms}(r)$	RMS value of raw time signal
y_{pk-pk}	Peak to peak value of time signal
$\bar{y}$ and $\Delta\bar{x}$	Mean value of time signal
d_k	Difference signal
$\bar{d}$	Mean of the difference signal
$y_{rms}(d)$	RMS value of difference signal
Δx_k	Difference between $(i)^{th}$ and $(i+1)^{th}$ value of the signal
A_k	The amplitude of k^{th} harmonic
r_{kj}	kth sample point of the residual signal
$\overline{r_j}$	Mean of jth sample point of the residual signal
j	Count of current time signal
E_k	k^{th} sample point of an envelope signal
$\overline{E_j}$	Mean of jth sample point of enveloping signal
S_{std}	The standard deviation of the time-domain signal
$sk_{gearmesh}$	The amplitude of the k^{th} sideband around fundamental gear mesh frequency
$s_{\max k}$	the k^{th} maximum linear amplitude of the sideband
P	Power distribution pattern
$\bar{P}$	Mean of the power distribution pattern
p_α	(%) of energy of the αth frequency band of the signal of WPT or EMD
SD	Standard deviation of power distribution pattern
RH	Residual vibration signal for the healthy condition
$\overline{RH}$	Mean residual vibration signal for the healthy condition
R	Residual vibration signal for current state condition
$\bar{R}$	Mean of residual vibration signal for current state condition
f_n	Frequency value of nth spectrum line
Y_n	Frequency value of nth frequency spectrum
RMSF	Root mean square frequency
MF	Mean frequency
STDF	Standard deviation frequency
x(t)	Time domain signal

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