Review on Various Techniques Used in Condition Monitoring of Gears and Shafts

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Abstract – *Determination of the gear and shaft defects from the vibration analysis is always an area of research, because vibration signals from a gear pair and rotating shaft are complex in nature and not easy to interpret. Predicting these defects by analyzing changes in vibration signal of these components (gear pair and shaft) in operation is a very reliable method. Therefore, a suitable vibration signal processing technique is necessary to extract defect information. There are many methods for determining the defects in the gear pairs and shafts but out of them spectral and cestrum analysis methods for gears and orbital analysis method for shaft are best and simple to interpret. Analysis of axis orbit is extremely important for monitoring faults in rotary machines and making an associated diagnosis for repair. This paper discusses how various gear pair and shaft defects can be diagnosed by spectral, cepstral and orbital analysis respectively.*

Key Words: **Condition Monitoring, Spectrum, Cepstrum, Vibration, Signal Processing.**

1. INTRODUCTION

As gears have different faults. Early identification of such faults is essential because if a machine gear fails it might damage other important parts also. So, to save cost, increase the machine life time and to maintain procedures of the machine, premature fault detection of gears is needed. Faults identification and prediction is done by analysing vibration signals taken from the machine gear box casing. To analyse the vibration data signal various signal processing methods were developed. Those methods were developed on time domain, frequency domain and time-frequency domain. Analysis of vibration signals is done by comparing signals when the system was healthy and currents signals. Before a signal to be analysed signal conditioning has to be done. The vibration data signal might contain noises. Before the signal is to be processed those unwanted signals have to be removed from the vibration data set. There are several signal conditioning techniques that used in signal processing. Signal correction, low pass filtering, amplifying, time synchronize averaging and mean value removal are some of those signal conditioning methods. Vibration signals are not measured when the machine is accelerating. Because of the acceleration Shaft speeds vary and therefore the vibration signals will be inaccurate.

Monitoring the state of rotary induction machines and diagnosing incipient faults is necessary to increase the reliability of productive systems [1]. The axis orbit is one of the most important tools when considering vibration analysis of a rotating machine and different axis orbits reflect various running states and provide rotor failure information. However, traditional methods used to identify the axis orbit have serious fault diagnosis limits on an automation level [2, 3]. The orbit diagram is a graphical tool for monitoring the orbit and is described by the centre of the machine's axis along its radial plane. The orbit is plotted using the alternate current level of the quadrature proximity sensors [1, 2]. Orbital analysis focuses on the trajectory of the centre of the axis in the reading plane of a pair of proximity sensors that are mounted rigidly on the machine frame. Thus, the orbit represents the trajectory of the centre of the axis relative to the structure of the machine. The graph is easy to interpret and provides adequate information about the orbit for use in effectively diagnosing rotating machine faults.

2. BACKGROUND

2.1 Vibration Analysis

Vibration analysis is applied to rotating equipment, such as gas turbines, pumps, motors, compressors, papermaking machines, or gearboxes, and is used to determine the mechanical condition of the equipment. The main advantage of this type of analysis is that problems can be identified before they become critical, and analysis can be conducted using continuous monitoring (online or wireless) or at scheduled intervals (offline) through manual collection. A vibration analysis system generally contains four components [1]. i) sensors for data collection that are usually of an accelerometer type ii) a signal analyzer iii) compatible software and iv) a computer for data analysis and storage.

2.2 Orbital Analysis

The time signal provides important and useful information; however, if the axis only moves on a two-dimensional path, the information obtained is limited. To monitor such movement, one sensor needs to be installed perpendicular to the second sensor, and an inductive proximity sensor is generally used in this respect. After installing the second sensor, certain conditions need to be met to determine the movement of the center of the axis in this plane. This information obtained can be presented using two individual time signals respectively for each sensor, but ideally a graph can be drawn that represents the two dimensions of the axis movement [2]. Fig. 1 shows the orthogonal installation of sensors used in orbital analysis.

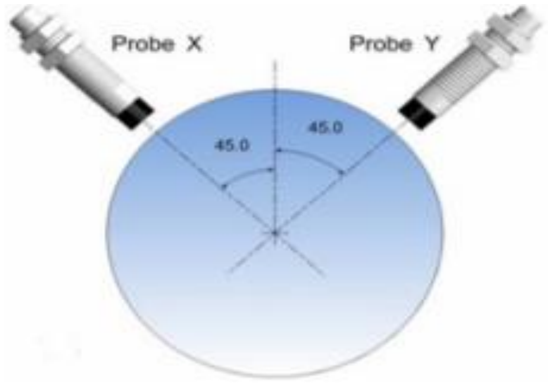

Fig. 1: Two proximity sensors installed orthogonally

The orbit represents the trajectory of the centre of the axis of a pair of proximity sensors in a reading plane. The lateral vibration signals of the rotor indicate oscillating movements of the shaft in one direction only, but when a sensor is positioned perpendicular to the other, it is possible to follow the two-dimensional movement of the vibration by looking at the path along which the centre of the rotor moves. This movement in a plane is known as the orbital motion of the rotor. The orbit of a rotor represents the path of the centre line of a given axis relative to the pair of perpendicular sensors installed therein.

3. TERMINOLOGIES

3.1 Spectrum: It describes the signal's magnitude and phase characteristics as a function of frequency.

3.2 Gear Mesh Frequency (GMF) or Tooth Mesh Frequency: It is the product of the number of teeth on the gear and the running speed of the gear.

GMF = Number of Teeth * RPM.

3.3 GMF Harmonics: A harmonic is a wave with a frequency that is a positive integer multiple of the frequency of the original wave (1x GMF).
The multiples of 1xGMF are respectively given as 2xGMF, 3xGMF, 4xGMF and so on.

3.4 Modulation Effects: Components at other frequencies, in particular sidebands around the tooth meshing harmonics, can usually be explained by modulation of the otherwise uniform tooth meshing vibration.

As an example, because of the load dependence of the tooth deflection effect, any fluctuations in the tooth loading (for example caused by misalignment) would tend to cause the vibration amplitude to vary, thus giving an amplitude modulation. At the same time these fluctuations in tooth loading must give fluctuations in angular velocity of gears and result in frequency modulation.

Both amplitude and frequency modulation at a certain frequency give rise to sidebands spaced around the basic frequency (and its harmonics if it is distorted) with a spacing equal to the modulating frequency, and thus this sideband spacing contains very valuable diagnostic information as to the source of a modulation effect, often tracing it to a particular wheel in a complex gearbox.

3.5 Sidebands: A sideband is a band of frequencies higher than or lower than the carrier frequency, those are the result of the modulation process.

3.6 Cepstrum: Cepstrum is the Inverse Fourier Transform (IFT) of the logarithm of estimated signal spectrum.

3.7 Accelerometer: An accelerometer is a device that measures the vibration, or acceleration of motion of a structure. The force caused by vibration or a change in motion (acceleration) causes the mass to "squeeze" the piezoelectric material which produces an electrical charge that is proportional to the force exerted upon it.

4. DETECTION OF GEAR FAULTS

As mentioned above gears may fail because of different conditions and there are different gear faults also. Most of the gear faults are happened because of fatigue conditions of the gear. Early detection of such faults is very important because it will save the machine, time, and money.

Analysis of gear faults is done by using various methods. Mainly in vibration analysis of a signal spectrum and cepstrum analysis techniques are used. These are the simplest methods of detecting gear faults.

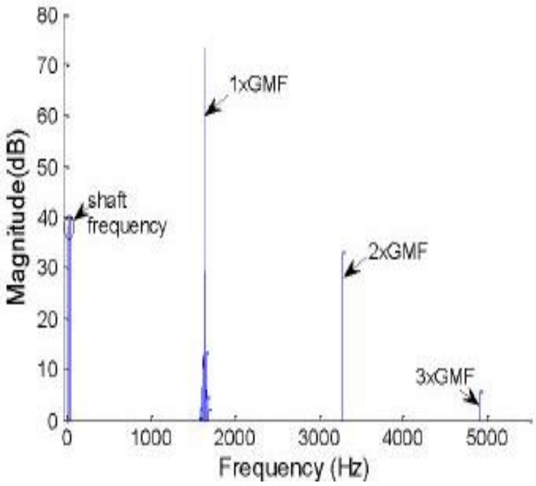

Fig. 2: Spectral signal of a gear

Cepstrum analysis is a development of the spectrum analysis. Cepstrum analysis has a good resolution than the spectrum analysis [5]. Spectrum analysis is done by using fast Fourier transform and the X axis of the amplitude (on Y axis) graph of the spectrum analysis labelled as frequency as shown in Fig. 2. But in cepstral analysis the cepstrum analysis graph represents the logarithmic value of the amplitude and the frequency of the amplitude spectrum is replaced by quefrency in the cepstral analysis graph as shown in Fig. 3. Quefrency represents modulation period and the reciprocal of the signals modulating frequency.

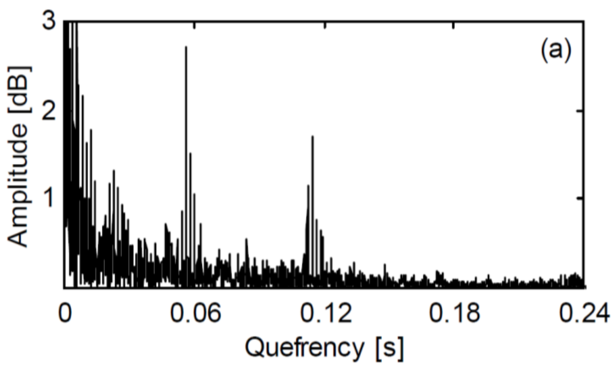

Fig. 3: Cepstrum signal of a gear

4.1 Gear Wear

In a frequency spectrum of a gear which has wear typically gives the rotating shaft frequency of the gear, gear meshing frequency and harmonics of those frequency. With respect to the development of the gear wear in the gear wheel over the time the second and third gear mesh harmonics increase more significantly than the noises of the shaft rotating frequency and first gear mesh frequencies.

The following Fig. 4 shows a healthy gear frequency spectrum in which gear shaft and pinion shaft rotation frequencies are 20 Hz and 47 Hz respectively.

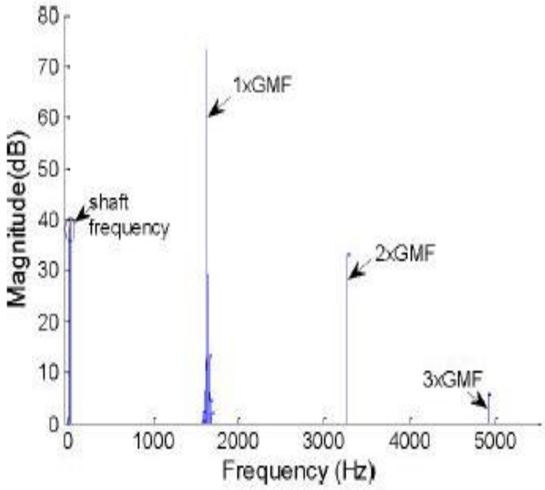

Fig. 4 : Frequency spectrum of healthy gear

The table 1 show variations between several wear failure signals that taken in several intervals of the gear fault. There are six different signals. As we can see in the table the second and the third GMF harmonics of the gear increase when the gear wear increase [5]. Anyhow, the gear mesh frequency is not changed.

If gear meshing second and third harmonics is increasing than GMF states that the gear has wearing problem. With the increase in second and third harmonics amplitude the gear wear also increases.

Table 1: Faulty gear signal with wear [5]

GMF	Normal(dB)	A (dB)	B (dB)	C (dB)	D (dB)	E (dB)	F (dB)
1st	73.2	73.2	73.2	73.2	73.2	73.2	73.2
2nd	33.2	45.2	52.3	57.3	61.2	64.3	67
3rd	5.6	12.6	17.6	21.5	24.7	27.3	29.7

4.2 Gear Misalignment Identification

Frequency spectrum of a healthy gear typically gives shaft frequency, gear mesh frequency and its harmonics. Gear misalignment is a considerable problem for gear because it could be the beginning for some serious faults in gears. So, by minimizing the misalignment of gears we can protect the gear from serious injurious. The following Fig. 5 represent frequency spectrum of a healthy gear.

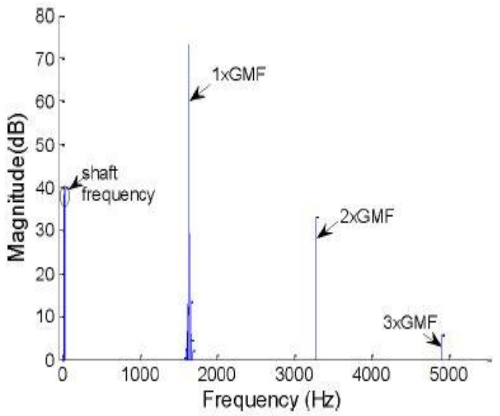

Fig. 5 : Frequency spectram of healthy gear

Table 2: Faulty gear signal with misalignment [5]

	Normal (dB)	A (dB)	B (dB)	C (dB)	D (dB)	E (dB)	F (dB)	G (dB)
1st GMF	73.2	35.4	35.4	35.4	35.4	35.4	35.4	35.4
2nd GMF	33.2	75.4	77.4	79.2	80.9	82.4	83.8	85
3rd GMF	5.6	39.6	39.6	39.6	39.6	39.6	39.6	39.6
1st SB	0	14	14	14	14	14	14	14
2nd SB	0	34	35	36	36.7	37.5	38	38.8
3rd SB	0	16	16	16	16	16	16	16

When the misalignment occurs in gear special changes happens in the frequency spectrum. Side band occurrence around the GMF and other GMF harmonics is a common phenomenon for misalignment of gears [5]. The above table 2 represents seven frequency signals of same gear pair system having misalignment, each taken after certain interval of time. It can be seen that in every signal, the 2nd gear meshing frequency and its side band are changing.

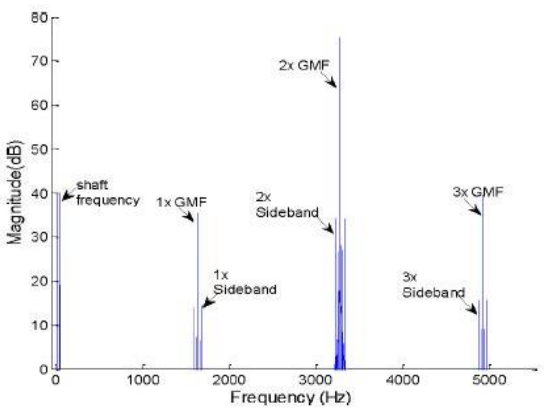

Fig. 6: Frequency spectrum of misaligned gear

The Fig. 6 demonstrates how the frequency spectrum of misalignment faulting gear differs from the original gear frequency spectrum. As mentioned above in the figure we can clearly identify the fundamental frequencies of the gear and its side bands. As in the table 2 we can see that the second harmonic GMF frequency has higher amplitude than the other component of the spectrum. When the gear misalignment increases its second gear harmonic frequencies and its side bands are also assumed to be increased.

4.3 Gear Tooth Crack

Gear tooth crack and broken tooth problem appears mostly because of gear fatigue. If there is a single crack on a gear tooth, when contacting that tooth there will be a little noise on the frequency spectrum. If the fault intensity is larger the fault duration will be also larger than the single crack problem. So there will be a family of sidebands on the frequency spectrum with equal spacing.

Fig. 7: Gears with tooth defects

Fig. 7 shows three types of gear crack faults considered, first one shows a gear with a one tooth crack, second one is a gear with one tooth broken and third one is two teeth broken gear. Following fig. 8 shows Frequency spectrums of healthy gear, one tooth crack gear, one tooth broken gear and two teeth broken gear. Broken tooth problem happens because of gear tooth cracks.

(fm1, fm2 are gear meshing frequencies, fr1, fr2, fr3 are shaft frequencies of input, pinion, and output shaft)

Fig. 8 (a) gives the healthy gear frequencies of the gear. 60Hz, 180 Hz and 300Hz are some ghost frequencies appeared in the gear box.

In the gear crack case fm1 with sidebands and fr3 rotation frequency appear in the frequency spectrum than the healthy gear frequency spectrum (fig. b). In the gear one tooth and two teeth broken cases fm1 and fm2 with sidebands and fr3 appears in the frequency spectrums of two vibration signals (fig. c & d).

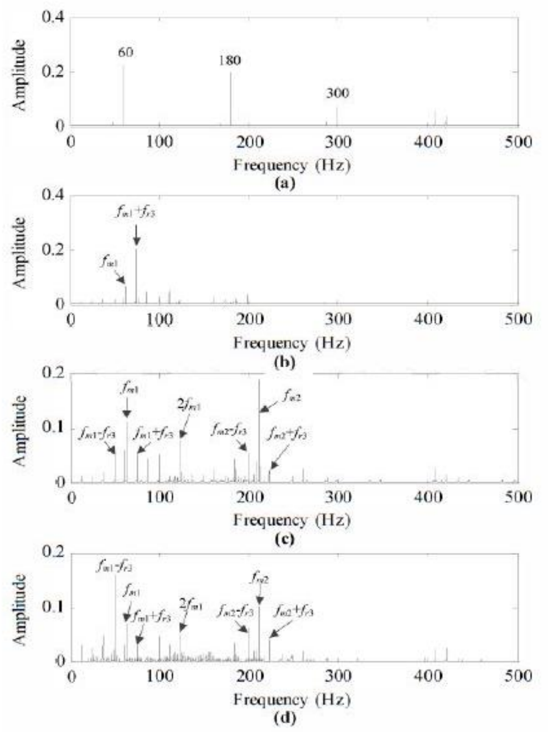

Fig. 8: a). Single tooth crack gear. B) One tooth broken gear. C) Two teeth broken gear [5]

4.4 Gear Surface Pitting

Detection of surface pitting in gears is not an easy task for human eye. So further transformations of wave analysis need for those examinations. Fig. 9 below shows a healthy gear frequency spectrum and frequency spectrum of a same type of gear that has pitting failure is shown in Fig. 10. The following gear is meshed with an input shat speed of 3000 rpm and 50 Nm of load. In the healthy gear, constant gear teeth meshing frequency is generated with very low vibration amplitudes. Gear meshing frequencies increase when a gear fault develops. So, when comparing two frequency spectrums we can clearly see that there is rise in amplitude in case of the fault signal spectrum. The value that increased the most is the 2500 Hz frequency.

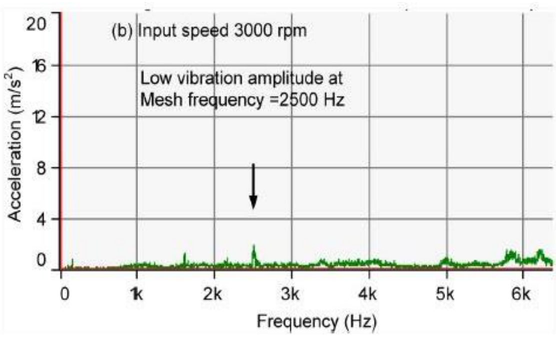

Fig. 9: Frequency spectrum of healthy gear

Increase of certain frequency amplitude might be a gear misalignment fault. To identify such problem advanced analysis is needed. Unless in the gear misalignment case in here we can see a huge amplification in the 2500 Hz frequency. That is because gear meshing is not smoother in this case than the healthy gear. When gear pitting happens, gear meshing is not smoother because gear tooth surface has small damages. So, this case can be identified as a gear pitting case but for further study advanced technological methods are needed [5][8].

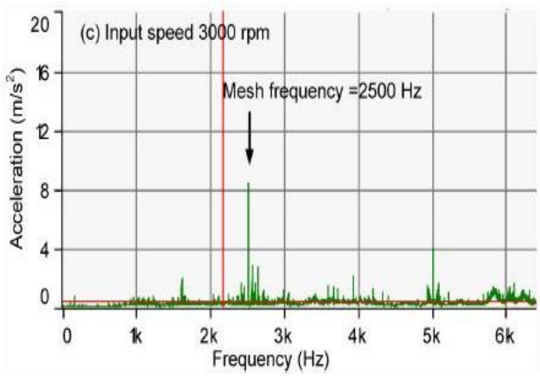

Fig. 10: Frequency spectrum of gear pitting fault

As discussed above, with the help of spectral analysis we can detect the type of fault present in the given system. So, if the cepstra of the same signal is considered then it became easier to identify the position of the fault i.e. on which gear actually the fault is present. This can be illustrated as discussed in next point.

5. DETERMINING THE POSITION OF THE FAULT WITH CEPSTRUM SIGNAL

With the help of spectral signal, we can identify the nature of fault but in order to find the exact location of that fault i.e. on which gear the fault is exactly present in the gearbox system cepstral analysis is required. The cepstrum can be considered as an aid to the interpretation of the spectrum, in particular with respect to sideband families, because it presents the information in a more efficient manner. Small changes in positioning of an accelerometer, for example, can modify the overall shape of the spectrum signal but the cepstrum signal is least affected because the cepstrum component corresponding to a given sideband spacing is an average sideband height over the whole spectrum and is much less likely to be affected.

Fig. 11 illustrates a typical case with spectra taken from two separate measurement points on the same gearbox, but representing the same internal condition.

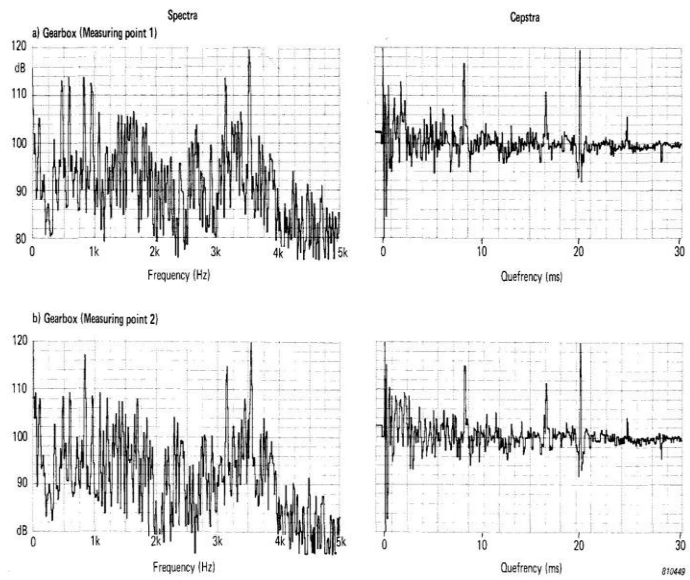

Fig. 11: Spectral and cepstral signals of same system with different accelerometer position [7]

The spectra are quite different in shape (for example at 2.6 kHz there is a peak in one spectrum and a trough in the other) but the significant cepstrum components are almost identical. Thus, diagnosing the fault position from spectrum signal may be misleading but cepstral signals can easily represent the fault position with greater efficiency.

6. DETECTION OF SHAFT FAULTS

Orbital analysis is used for determining of shaft faults, as of now orbital analysis is only used for determining the failures of rotating elements such as shafts, turbines, gearboxes, etc, because only balancing and misalignment are determined by this method and other failures detection using this method is under a case study.

6.1 Orbital Pattern Building

Orbits are constructed using two vibration signals, which are plotted in a (x, y) chart. In order to create an orbit, two different displacement signals x1(t) and x2(t) are measured orthogonally in the same rotor chassis and then are plotted orthogonally as f (x, y) =f (x1, x2). However, a signal pre-processing treatment is needed for avoiding undesirable effects such as noise or spurious frequencies. First, measured vibration signals are pre-processed separately in order to preserve their particular features. Shape orbits are built using displacement signals, that were measured indirectly by acquiring two accelerometer vibration signals placed orthogonally; nevertheless, as an accelerometer measures vibration in acceleration units a(t), the measured signals must be transformed to positioning units. This process can be performed when the acceleration of one signal is transformed into velocity and then into displacement by integrating the acceleration signal in time domain according to the following definitions [2]:

$$v(t) = \int_0^t a(t)\,dt + v_0$$
$$x(t) = \int_0^t v(t)\,dt + d_0$$

Vibration signals in displacement units are compounded by several harmonics; each can be related with the normal operation or with a fault. For unbalance and misalignment faults, the main harmonic is extracted for creating the orbits; other harmonics can distort the orbit shape changing notably the main characteristic of a fault shape. Additionally, the orbit shape can be affected by the effects of many other types of faults; however, only unbalances and misalignments are analysed in this work and other fault still are a case study, so they are treated as undesirable harmonics. Therefore, those undesirable harmonics must be removed in order to have a good quality orbit. The following expression defines the filter equation used for cleaning the displacement signal [2]:

$$s(n) = \sum_{k=0}^{N-1} h(k)x(n-k)$$

Where s(n) is the filtered signal and h(k) is the transfer function.
Orbits shapes have correspondence with rotating machine faults and they have some specific characteristics that can be useful for pattern classification, Fig. 12 shows the most representative shapes for the described faults, where a perfect circular shape represents a good condition of rotating machine, an elliptical shape corresponds to an unbalanced fault and a distorted ellipse corresponds to a misalignment fault. The orbit shape suggests the fault type. In this sense, we use the shape orbit as a particular pattern to be classified into the described faults.

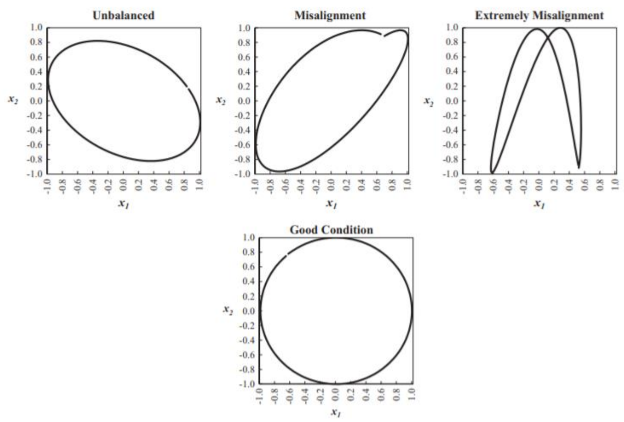

Fig. 12: Examples of orbit shapes that correspond to different faults [2].

Some examples of machine shaft imbalance, misalignment of machine faults from some experimental analysis [1] are given below, so that various faults can be reviewed.

6.2 Machine Running Imbalanced

Fig. 13 shows the successive waveform changes occurring from the system due to imbalance. A comparison between these results and the reference results of the experimental system, shows that a considerable increase in the 1X forward component occurred (from 19.25 to 73.42 µm) and that this increase was also recorded at 1X reverse (3,211 to 18,55 µm). These results are evidence that the profile of the orbit Fig. 13 b became slightly more elliptical.

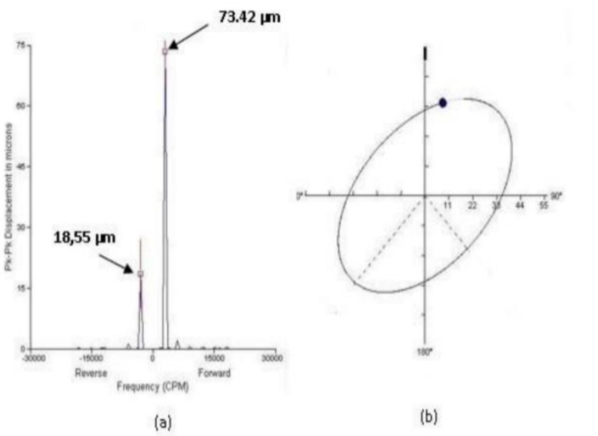

Fig. 13: Full spectrum (a) and orbit graph imbalanced machine (b) [1].

6.3 Applied Load and Misalignment

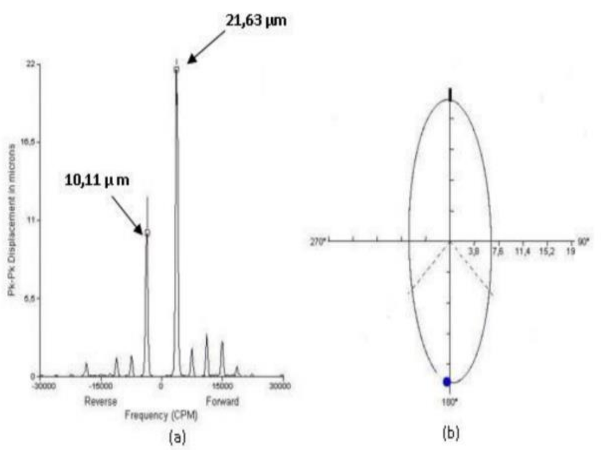

Fig. 14: Full spectrum (a) and orbit graph misalignment machine (b) [1].

The second largest problem with rotating machines is the high temperatures recorded on bearings; these are almost always related to high dynamic or static radial loads that may result from the rotor's own weight, mechanical aspects (such as coupling defects), imbalances, or misalignment and the profile of the filtered orbit at 1X finally adopts a pronounced elliptical profile. A comparison of the results presented in Fig. 14 with the reference results, shows that there was an increase in the 1X forward component (19.25 to 21.63 µm) and a considerable increase in the reverse component (3.211 to 10.11 µm). It is therefore evident that the main symptom indicative of misalignment is the ellipticity of the profile adopted by the orbit. This can be accordingly seen in the presence and growth of the 1X reverse component; in addition, harmonics 2X and 3X of the speed of rotation (reverse and forward) appear.

7. CONCLUSION

Frequency domain and time domain analysis are very good tools to detect various defects in gears. Spectral analysis (FFT form of vibration signal) can detect the nature of fault present. Cepstral analysis over spectral analysis is very good technique to diagnose the source of faulty signals i.e. the position of defect. Shaft orbit is promising feature source for rotating machinery prognosis. Abnormal changes in the ellipticity of the orbit and the direction of the vibration precession are significant symptoms of some types of fault. This Orbital Analysis enables identification of the type of fault likely to have occurred by analyzing the altered pattern of the components of the orbit spectrum. Based on current information available for orbital analysis it can be concluded that new techniques must be developed in order to discover new orbit representations according to other faults, including several aspects as new harmonics or different ways for sensor positioning.

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