AN OVERVIEW OF FAULT DETECTION METHODS FOR TRANSMISSION SYSTEM COMPONENTS USING VIBRATION ANALYSIS

L.S.Dhamande[1], Dr.H.N.Kudal[2]

[1]Associate Professor, SRES's College of Engineering, Kopargaon-423603(University of Pune, Pune)
Email:lsdhamande@rediffmail.com
[2]Principal, P. D. V. V. P., College of Engineering, Ahemadnagar

ABSTRACT: The purpose of this paper is to review the literature on Health or Condition monitoring methods for detection of damage in different transmission system components. The transmission system is the heart of any industrial rotating machinery hence the health of machine depends on the performance of it. A good Condition Based Maintenance (CBM) reduces downtime, spares inventory, maintenance cost, and safety hazard. It consists of three main steps: data acquisition, data processing and maintenance decision-making.

This paper outlines the important techniques used in damage detection of rotor shafts, gears, bearings and beams etc. using vibration measurement in time and frequency domain. Also it attempts to summarise and review the recent research and developments in diagnostics and prognostics of mechanical systems implementing CBM with emphasis on models, algorithms and technologies for data processing and maintenance decision-making. The main intention of this work is to develop a methodology which will be applicable to the transmission system as a whole and can detect the damage more effectively. The paper concludes with a brief discussion on current practices and possible future trends of CBM as well as challenges and opportunities in this field.

Keywords - *Condition monitoring, damage detection, Transmission system, Time-frequency analysis Vibration Analysis,.*

1. INTRODUCTION:

All machines with moving parts give rise to sound and vibration. Each machine has a specific vibration signature related to the construction and the state of the machine. The vibration signature of the machine will also change if the state changes. A change in the vibration signature can be used to detect incipient defects before they become critical. This is the basics of many condition monitoring methods. Condition monitoring can save money through increased maintenance efficiency and by reducing the risk of serious accidents by preventing breakdowns.

Reliability has always been an important aspect in the assessment of industrial products and/or equipments. Good product design is of course essential for products with high reliability. However, no matter how good the product design is, products deteriorate over time since they are operating under certain stress or load in the real environment, often involving randomness. Maintenance has, thus, been introduced as an efficient way to assure a satisfactory level of reliability during the useful life of a physical asset [1].

Gears, shafts, pulleys and bearings and beams are parts of almost every rotating machine and they are inherently subjected to dynamic contact forces with high amplitudes. In the region close to the contact surfaces the material stress is locally very high. Thus, after sometime of operation a localized defect growing with time will appear. The defects may be localized surface damage, wear or inadequate lubrication, Tooth root cracks, missing material of tooth, Pitch error, Eccentricity, etc. At the same time there may be different faults which causes damage to the mechanical system if not controlled, like Axial rotor asymmetry, Flexible coupling misalignment, Rigid coupling misalignment , Bearing misalignment, Transverse crack, Rotor to stator rub, Loosening bearing bushes Etc. Vibration signatures of Non-defective components are characterized by particular amplitude and frequency. If a defect/fault is present in the system, depending upon the location, it will modify the vibration signature, which is a basic assumption in machine condition monitoring. The primary problem is that of resonance, where response levels under dynamic loading can be 100 or 1000 times greater than the levels resulting from static loading of the same magnitude [2].

A significant work has been published, mostly in the last 30 years, on the failure, damage detection and diagnosis of mechanical equipments by vibration analysis methods. Some of these works have also been reviewed by researchers. Aiwina Heng *et al* [1] presented a detailed review of rotating machinery prognostics. Major problem in any machinery is control of vibration amplitude called resonance is reviewed by D.J. Ewins with respect to aero engines and rotating machinery [2]. Y. J. Yan *et al* [3] have studied the development in vibration based structural damage detection methods. Abdurrahman S. Sait *et al* [4] reviewed in his paper all the different methods used for analyzing the vibration signature obtained from Gear box and rotating machinery. N. Tandon, A. Choudhury [5] have reviewed different vibration and acoustic methods, such as vibration measurements in time and frequency domains, sound measurements, the shock pulse method and the acoustic emission technique, for condition monitoring of rolling bearings. We determine the presence of defect in a machine to know the remaining life of machine, the methodology of the same is explained by Aiwina Heng *et al* [1] in detail. Therefore, the objective of the present study is to update these reviews by incorporating recent works and the advanced techniques adopted in defect detection of transmission system components.

1.1 Damage detection of Transmission system components:

Many researchers have worked on the detection of presence, depth and location of crack in the rotor which may be a gear box shaft, a pulley mounted on shaft etc. by using different techniques. D. Dane Quinn *et al* [7] have investigated the presence of crack by using active magnetic bearing as input and output is determined by using proximity probe. The magnitude of time dependent stiffness arising from breathing mode of cracked shaft is obtained by using multiple scale analysis, which gives a combination resonance that only occurs in the presence of a breathing crack. Mohammad A. AL-Shudeifat *et al.* [8] has introduced an efficient technique to study the effect of crack depth of a rotor-bearing-disk system on vibration amplitudes and whirl orbit shapes using a general harmonic balance technique and experimental verification. While some researchers worked on detection of presence, depth and location of crack in a rotor using different statistical techniques such as autoregressive model [9]-[12]. Since more than one fault may be generated in any component at any time hence the effect of combined fault on the vibration signature of rotor is studied [13] at the same time what is the effect of faults on the different parameters of the system are analysed by measuring Vibration, AE, and oil debris monitoring of lubricating oil (ODM) data. This increases the diagnostic capacity and reliability of the condition monitoring scheme for rotating machinery [14].

1.2 Stages of development in maintenance strategy:

Current maintenance strategies have progressed from breakdown maintenance, to preventive maintenance, then to condition-based maintenance (CBM) managed by experts, and lately towards a futuristic view of intelligent predictive maintenance systems. The earliest maintenance technique is basically a breakdown maintenance, which takes place only at breakdowns. To prevent catastrophic failures and emergency shutdowns, a later maintenance technique is time-based preventive maintenance, which sets a periodic interval to perform preventive maintenance regardless of the health status of a physical asset. With the rapid development of modern technology, products have become more and more complex while better quality and higher reliability are required. This makes the cost of preventive maintenance higher and higher. Eventually, preventive maintenance has become a major expense of many industrial companies. Therefore, more efficient maintenance approaches such as condition-based maintenance (CBM) are being implemented to handle the situation.99% of mechanical failure are giving a sign of its occurrences in advance and hence if we monitor the condition of machine we definitely get the evidence of failure before it occurs[3].

2. CONDITION MONITORING:

The main purpose of condition monitoring is the detection of damage at an early stage in rotating machinery. At present use of non-destructive examination (NDE) method to detect damage status of engineering structures has become a hotspot and difficult issue. Recently, NDE technique is widely applied in industries, such as astronautics, aviation, space vehicle, power plant equipment, architecture, metallurgy and mechanical manufacture, etc.

Generally, structural damage detection can be classified as local-damage detection and global-damage detection. Local-damage detection techniques refer to non-destructive testing (NDT) as CT scanning, Ultrasonic, Eddy current, liquid penetrant, Magnetic particle, Visual check, Time of flight diffraction etc. These are mainly used to detect local damage in structures, and it can determine damage existence and its location. Local damage detection methods utilise only data obtained from the damaged structure. Baseline data and theoretical models of the undamaged structure are not used. These are the main advantages of local damage detection. Local damage detection is very effective for small and regular structures, such as pressure vessels. However, for the large and complicated structures in invisible or closed environments, it is very difficult to detect damage using local damage detection method [3].

In order to detect damage throughout the whole structure, especially some large, complicated structures, a methodology called global structural damage detection has been proposed. Most of the recent work is focused on more advanced techniques such as angular motion analysis, vibration-based analysis, model-based analysis and mathematical modeling. The vibration based method is the most effective hence it is discussed in more detail. The basic principle of vibration based method can be explained as follows. For any structure, it can be taken as a dynamics system with stiffness, mass and damping. Once some damages emerge in the structure, the structural parameters will change, and the frequency-response function and modal parameters of the structural system will also change. Thus, the change of the structural modal parameters can be taken as the signal of early damage occurrence in the structural system.

2.1 Vibration based damage detection methods of condition monitoring:

Damage can be defined as changes appearing in a system that may affect its current or future performance. The definition of damage can also be limited to changes to the material and/or geometric properties of the system, including changes to the boundary conditions and system connectivity, which adversely affect the current or future performance of that system. Vibration Based Methods can be classified as Traditional type methods and Modern methods.

2.1.1 Traditional Type Methods:

The different traditional type methods which utilize mechanics characteristics of structure determine the damage on the basis of change in natural frequency, change of structural flexibility/stiffness, change in modal damping and change in modal strain energy; change in mode shapes and also on the basis of statistic information and power flow. Since these methods requires long experimentation using sophisticated instruments hence these are time consuming and expensive also their dependence on properties of individual copmponent make it unsuitable to give universal methodology. At the same time these are not sensitive to tiny damage [3].

2.1.2 Modern Vibration Based Methods:

Vibration-based techniques extract the features which gives an idea about the presence of the damage hence called as feature extraction techniques which can be divided into two main different processing groups. These two main processing groups are: Time-Statistical Analysis and Time-Frequency Analysis. Furthermore, each one of these processing groups is also divided into subgroups as shown in Fig. 1 below. Each individual technique is listed and explained as follows.

2.1.2.1 Time-statistical analysis:

Time-statistical analysis is one of the traditional methods used in transmission system components failure detection and condition monitoring. Since vibration signature obtained from any machinery

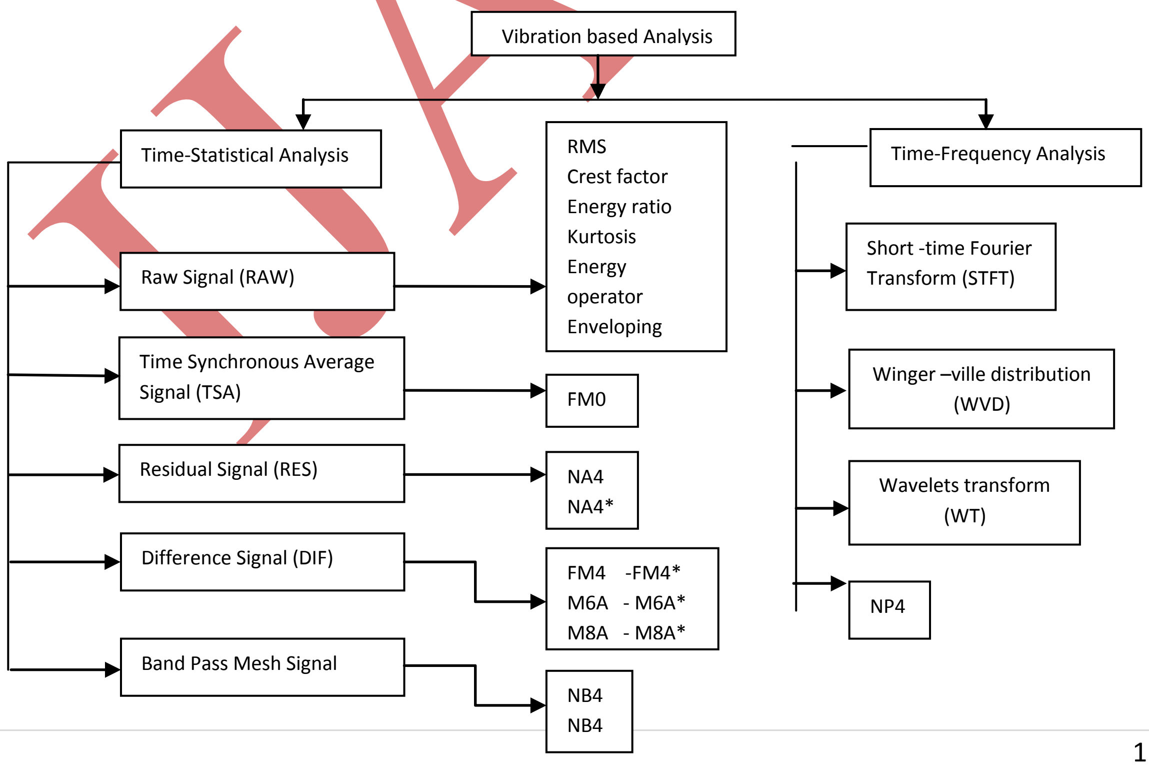

Figure 1. Classification of Vibration Based Analysis Techniques and Parameters

consist of noise which needs to be filtered hence denoising methods based on wavelet analysis and self-adaptive noise cancellation (SANC) in conjunction with envelope analysis for feature extraction is used [15]-[16]. Figure 2 below shows the processing flow for feature extraction techniques [4]. There are five different processing subgroups fall in this category of analysis as follows:

a) Raw signal: It indicates elements that are computed from the raw or trained signal collected by the sensor. Training the signal can be done by multiplying all the data points by a calibration constant that is based on the accelerometer used. There are seven techniques fall in this subgroup

1. RMS- It is the measure of the power continent in the vibration signature. The RMS for a sine wave can be defined to be 0.707 times the amplitude of the signal. Useful for detecting unbalanced Rotating elements or sinusoidal waves

2. Crest factor- The crest factor can be defined as the ratio of the positive peak value of the input signal to the RMS level. Useful for defects in rotating machinery, tooth damage in gearbox, defect in outer race of bearing.

3. Energy ratio- It is the ratio of the RMS of the difference signal and the RMS of the signal of the regular meshing component. Useful for detecting heavy uniform wear

4. Kurtosis- The kurtosis can be defined as the fourth normalized moment of the signal. Measure of no. of amplitude of peaks in signal, for gearbox in good condition K=3, used for bearing also [5].

5. Energy operator-Squaring input signal and subtracting the product of point before and after from squared signal.

6. Enveloping-The enveloping technique can be applied by extracting the frequency of the envelope, and then the damaged part of the bearing or gearbox can be detected.

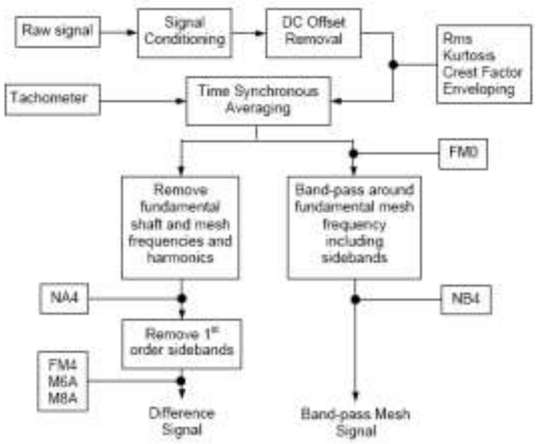

Figure 2. Processing Flow for Feature Extraction Techniques

7. Demodulation- Alternate High pass and low pass filtering of raw data.

b) Time synchronous averaging signal: A signal averaging process, to extract repetitive signal from additional noise. Parameter- FM0 is maximum peak-to-peak amplitude of the signal to the sum of the amplitudes of the meshing frequencies and their harmonics. It increases when heavy wear occurs, used for major changes in gear meshing.

c) Residual signal: It is applied by removing shaft components and gear meshing frequency in order to calculate the residual signal that contains the time synchronous averaged signal. Parameter-NA4 and NA4*, NA4 is the ration of the kurtosis of a data record to the square of the average variance which is the mean value of the variance of all previous data records in the run ensemble.

d) Difference signal: Parameters used here are- FM4, FM4*, M6A, M6A*, M8A and M8A*.

FM4 is defined as the ratio of the kurtosis and the square of the variance of the difference signal, approximate value is 3.FM4* is similar to above but the denominator has the averaging effect of NA4*.M6A is more sensitive to peak in the difference signal since it uses the sixth moment normalized by the variance to the third power. It is used to detect surface damage on mechanical components. M6A* is same as the numerator in FM4, however the denominator has the averaging effect of NA4* and FM4*, M8A is same as FM4 and M6A but uses the eight moment normalized by the variance to the fourth power, M8A* is same as the numerator in FM4 however the denominator has the averaging effect of NA4*, FM4* and M6A*.

e) Band Pass Mesh Signal: The Band-pass mesh signal technique is applied by band-pass filtering the TSA signal around the primary gear meshing frequency. Then, the Hilbert transform is applied to the filtered signal which generates a complex time series of real and imaginary parts. Techniques fall in this subgroup are: NB4 and NB4* Parameter - NB4, NB4*. It is useful technique for localized tooth damage.

2.1.2.2 Time-Frequency Analysis:

A vibration signature consists of three components a sinusoidal component due to time varying loading, a broad-band impulsive component due to impact, and random noise. The trend displayed by the sinusoidal components are more observable in the frequency domain while the trends displayed by the broad-band impulsive components are more observable in the time domain hence to capture these trends, time-frequency analysis is considered. It involves

a) Short time Fourier Transform: Faults are detected by studying the energy distribution of signals over a time – frequency domain.

b) Winger-Ville distribution: It is obtained by taking sum of product of the signal before time t, and the reversed signal after time t. The damage can be purely identified by a visual inspection of the different patterns in the WVD plots which are generated by different types of faults.

c) Wavelet Transform: WT is a time-frequency analysis technique and has similar characteristics to WVD. However, WT differs from Fourier transform in the way that it uses a new class of real and complex nonstationary basis function, termed wavelets, which can be independently dilate and shifted as a function of time. This technique has advantages that WT is useful for describing the local behavior of the signals and the frequency of the signal can be analyzed without losing the essential information of the time-domain.

d) NP4: It is derived from WVD Feature Extraction. It can be defined as the normalized kurtosis of the signal power. The novelty of the NP4 parameter is in application of the previously defined statistical parameter called kurtosis to the WVD data and its interpretation for gear fault detection. The calculation of NP4 does not require a comparison between a faulty and a healthy gear signals [5].

2.1.2.3 Modern methods and their advantages:

1. Less dependent on experimentation, few points are to be measured [3].
2. It can provide universal methodology.
3. It is Sensitive to tiny damage.

2.1.3 Intelligent damage diagnosis methods [6]

These methods mainly use modern signal-processing techniques and artificial intelligence as analysis tool. Because of its universality and less dependence on structural shape, it is called intelligent damage diagnosis methods. Methods used are

2.1.3.1 Neural network method (NN):

The NN has been widely used in structural analysis because of its strong non-linear mapping ability. It is usually constructed by three layers, an input layer, a hidden layer and an output layer. The known feature information (NN input) and the corresponding status (NN output) of structural damage are taken as train samples to train the constructed NN. These damage information as train sample can be obtained by experiments or numerical simulations for a structure to be detected. When the NN has been well trained, one can input the experimentally measured real structural damage feature index into the trained NN, and the output of the trained NN will be able to give the location and severity of the structural damage.

2.1.3.2 Genetic algorithm method:

GA is a powerful universal tool to solve optimisation problem [6]. GA has high calculation efficiency in parallel data processing, and it can search for agminate solutions simultaneously. Thus, it is possible to obtain the global optimum solution. These methods detect the approximate location of the damage, even when practical considerations limit the number of on-site measurements to only a few. Even for complex structures, its damage location and degree can be easily detected.

3. PROCESS OF CONDITION MONITORING:

The condition monitoring uses information in the vibration signature of a machine to detect damage. A change in the vibration signature will imply a change in the state of the machine. The basic process of CBM can be divided into three steps; measurement of some relevant physical quantity, processing of the collected data to extract state features and finally comparison of the state features to reference values. Hence the key elements of CBM are

1. Data acquisition (i.e. the collection and storage of machine health information),
2. Data processing (i.e. the conditioning and feature extraction/selection of acquired data) and
3. Decision making (i.e. the recommendation of maintenance actions through diagnosis and/or prognosis) [1]. A measurement signal acquired from a machine in an industrial environment will often contain contributions from several different components as well as noise. One major challenge of condition monitoring is to pinpoint and extract the part of the signal that can be related to the damage state of the monitored component.

4. APPLICATIONS AND BENEFITS OF CONDITION MONITORING:

Condition monitoring methods can be used for both maintenance planning and production quality control. These two applications have both similarities and differences. In the maintenance application, condition monitoring can be used as a tool to enable maintenance planning based on early warnings. Beyond detection, some condition monitoring methods can also be used for diagnosing the type and forecasting the evolution of defects.

Increased automation and mechanisation have made computerised diagnostics and prognostics systems a valuable tool significantly reducing expensive downtime, spares inventory, maintenance labour costs and hazardous conditions.

5. METHODS FOR PREDICTING FAILURES IN MACHINERY

The existing methods for predicting rotating machinery failures can be grouped into the following categories:

1. Traditional reliability approaches
2. Prognostics approaches
3. Integrated approaches [1].

5.1 Traditional reliability approaches:

Previously maintenance scheduling is done by using the historical data of machine i.e. how a machine behaves throughout the year and what are the different events of failures of machine. Also how much time is required to repair the machine accordingly the prediction of the performance of machine and its reliability was calculated. These traditional approaches to reliability estimation are based on the distribution of event records of a population of identical units. The most popular parametric failure model is the Weibull distribution due to its ability to accommodate various types of behaviour including infant mortality in the ‘‘bath-tub’’ curve. These classical reliability approaches basically use historical time-to-failure data to estimate the population characteristics (such as mean-time-to-failure and probability of reliable operation). However, these approaches provide only general overall estimates for the entire population of identical units. This type of estimations is useful to manufacturers that produce units in high volumes but are of little value to end users

To estimate the current condition of an operating unit, a more ‘‘engineering’’ approach to reliability based on the actual change in unit health is necessary.

5.2 Prognostics approaches

Most of the existing prognostics models can be divided into two main categories: physics-based models and data-based models.

1. Physics-based prognostics models:

Physics-based models typically involve building technically comprehensive mathematical models to describe the physics of the system and failure modes, such as crack propagation and spall growth. These models attempt to combine system-specific mechanistic knowledge, defect growth formulas and Condition Monitoring (CM) data to provide ‘‘knowledge-rich’ ’prognosis output. A common physics-based approach is crack growth modeling. Crack growth modeling gives instantaneous defect size area from vibration data. For the case of gears, bearings the geometry of component, contact, load, fatigue, fracture properties, and material properties has dominant impact on accuracy of physics based models. Also this model is not suitable for industry application since the fault type in question is often unique from component to component and is hard to be identified without interrupting operation.

2. Data-driven prognostics models:

In this approaches mathematical models are derived directly from routinely collected CM data. They are built based on historical records and produce prediction outputs directly in terms of CM data. The conventional data-driven methods include simple projection models, such as exponential smoothing and autoregressive model. One major advantage of these techniques is the simplicity of their calculations. It was reported that none of the forecasting techniques was able to predict the sudden change in the life curve.

3. Integrated approaches:

In this approach prediction is based on both reliability and condition monitoring data. Different models are used such as the Proportional Hazards Model (PHM) for forecasting the reliability of rolling element bearings and engines. PHMs assume that hazard changes proportionately with covariates (asset condition in this case) and that the proportionality constant is the same at all time.

6. CONCLUDING REMARKS:

From a review of studies on different method for damage detection of different transmission system components it is seen that mostly vibration based methods are preferred. Although different techniques are developed for detection of local damage but still only few techniques in time domain such as overall RMS level, crest factor, kurtosis etc are used in the industries, and if they found the high level of vibration amplitude, without knowing the cause of vibration the machine is spared for maintenance action, which involves more maintenance cost and loss of production time. It means research is going on but only in laboratories and not in practical field. Hence the ultimate goal remains to establish reliable prognostics system that can be applied practically and benefit industries.

Vibration measurement in frequency domain is helpful in detecting the location of the defect also a very tiny damage can also be determined by new method of wavelet transform in time-frequency domain. At the same time noise measurement and acoustic emission measurement are also successfully applied in damage detection.

The Problems with modern methods yet to be solved /investigated are such as these methods rely on environmental excitation, tiny damage may be covered by noise and selection and construction of feature index of damage are very flexible and variable. Hence focus is needed in the following area of damage detection as, how to involve damage mechanism into dynamic model, about the Construction and extraction of feature index for small damage, development of damage detection technology using multidisciplinary intercrossing such as Artificial Intelligence, Neural Network, and Genetic Algorithm etc, optimization of position and Number of measurement sensors and nonlinear factors in damage detection.

REFERENCES

[1] Aiwina Heng, Sheng Zhang, Andy C. C. Tan, and Joseph Mathew, Rotating machinery prognostics: State of the art, challenges and opportunities, *Mechanical Systems and Signal Processing, 23, pp. 724–739, 2009*.

[2] D. J. Ewins, Control of vibration and resonance in aero engine and rotating machinery-An overview, *International Journal of Pressure Vessels and Piping*, 87, pp.504 - 510, 2010.

[3] Y. J. Yan, L. Cheng, Z. Y. Wu, and L. H. Yam, Development in vibration - based structural damage detection technique, *Mechanical Systems and Signal Processing, 21, pp. 2198– 2211, 2007*.

[4] Abdulrahman S. Sait, and Yahya I. Sharaf Eldeen , A Review of Gearbox Condition Monitoring Based on vibration Analysis Techniques Diagnostics and Prognostics, in *Proceedings of the Society for Experimental Mechanics Series,8,Volume 5, pp. 307-323, 2011.*

[5] N. Tandon, and A. Choudhury, A review of vibration and acoustic measurement methods for the detection of defects in rolling element bearings, *Tribology International, 32, pp. 469–480,1999.*

[6] B. Samanta, Artificial neural networks and genetic algorithms for gear fault detection, *Mechanical Systems and Signal Processing 18 , pp. 1273–1282,2004.*

[7] D. Dane Quinn, Girindra Mani, Mary E. F. Kasarda, Travis Bash, Daniel J. Inman, and R. Gordon Kirk, Damage Detection of a Rotating Cracked Shaft Using an Active Magnetic Bearing as a Force Actuator-Analysis and Experimental Verification , *IEEE/ASME transactions on mechatronics, vol. 10, no. 6, December, 2005.*

[8] Mohammad A. AL-Shudeifat, Eric A. Butcher, and Carl R. Stern, General harmonic balance solution of a cracked rotor-bearing-disk system for harmonic and sub-harmonic analysis: Analytical and experimental approach, *International Journal of Engineering Science, 48, pp. 921-935, 2010.*

[9] H.B. Dong, X.F.Chen, B. Li, K .Y .Qi, and Z. J. He, Rotor crack detection based on high-precision modal parameter identification method and wavelet finite element model, *Mechanical Systems and Signa Processing, 23, pp. 869–883,2009.*

[10] S. Da Silva and M. Dias Junior, Statistical damage detection in a stationary rotor systems through time series analysis, in *Proceedings of Latin American Applied Research, 37, pp. 243-246,2007.*

[11] Xiyang Wang , and Viliammn Makis, Autoregressive model-based gear shaft fault diagnosis using the Kolmogorov–Smirnov test, *Journal of Sound and Vibration, 327, pp. 413–423,2009.*

[12] Mohsen Nakhaeinejad, Jaewon Choi, and Michael D. Bryant, Model-based diagnostics and fault assessment of induction motors with incipient Faults, *in Proceedings of the Society for Experimental Mechanics, Series 8, Volume 5, pp.439-449, 2011.*

[13] H. Ma, T. Yu, X.P. Li, Z.H. Ren, and B. C. Wen, Extraction of combined fault features by time-frequency analysis in rotor systems,*12th IFToMM World Congress, Besancon (France), June18-21, 2007.*

[14] T.H. Loutas, D. Roulias, E. Pauly, and V. Kostopoulos, The combined use of vibration , acoustic emission and oil debris on-line monitoring towards a more effective condition monitoring of rotating machinery, *Mechanical systems and signal processing,25, pp.1339-1352,2011.*

[15] D. Ho and R. B. Randall, Optimisation of bearing diagnostic Techniques using simulated and actual Bearing fault signals, *Mechanical systems and signal processing,14(5), pp.763-788, 2000.*

[16] Jing Lin, Feature extraction based on Morlet wavelet and its application for mechanical fault Diagnosis, *Journal of sound and Vibration, 234(1), pp.135-148, 2000.*