# MACHINERY MONITORING USING VIBRATION SIGNAL ANALYSIS

**[1]ILHAN ASILTURK, [2]HALIT ASLANCI, [3]UGUR OZMEN**

Selçuk University, Faculty of Technology, Mechanical Engineering, Konya TURKEY
Email: iasilturk@yahoo.com, hlt_slnc@hotmail.com, ugur.ozmen@selcuk.edu.tr

**Abstract**— Temperature, vibration, noise, current, voltage, acoustic emission, etc., all of the measurements are used for machine condition monitoring. Measuring vibration signals is one of the non-destructive testing (NDT) methods that is widely used to detect machine faults. There are many studies to predict mechanical wear, fault and failure in this area for several decades. Signal processing techniques are used to obtain vital characteristic information from the vibration signals. This paper attempts to summarize the results of an evaluation of vibration analysis techniques as a method for diagnosis of gear faults. The most effective vibration techniques are discussed and experimentally compared, concerning an industrial gearbox. Their advantages and disadvantages have been shown.

**Keywords:** Vibration Signals, Monitoring, Predictive Maintenance

## I. INTRODUCTION

Machinery monitoring is the process of monitoring a parameter of condition in machinery, such that a significant change is indicative of a failure in development. Machine condition monitoring can be realized by monitoring following characteristics: temperature, vibration, noise, current, voltage, acoustic emission, wear, etc [1].
Vibration signals is a widely used for condition monitoring of rotating machines as one of the non-destructive methods. Online condition monitoring is essential for the reliability of rotating machine parts so that continuous information on their condition can be recorded and appropriate maintenance activities can be planned. All the machines while operating vibrate more or less, and with most of them the vibrations are unwanted and the effort is to minimize them. Gear and bearing components plays an important role in pumps, electric motors, internal combustion engines, presses, like rotating machinery etc.

Recently, early fault identification of gears and bearings may avoid unexpected failures of the many rotating machinery systems. Hence, it will increase the operational reliability and it will make the machine available. Fault diagnosis techniques are substantial for monitoring the status in gears and bearings [2]. Also on-line condition monitoring system is utilized major component of predictive maintenance in operation.

In order to improve rotating machine fault detection and identification algorithms, one significant issue is signal processing based fault feature extraction or quantification. Currently, vibration signal based techniques are the most widely used techniques in rotating machinery fault detection and diagnosis [3].
The purpose of this review is to present a summary about the results of an evaluation of vibration analysis techniques as a method for diagnosis of gear faults.

## II. FAULT DETECTION AND DIAGNOSIS FROM VIBRATION ANALYSIS

Misalignment, unbalance, distortion and looseness, defective bearings, gearing and coupling in accuracies, various form of resonance, critical speeds, reciprocating forces, bad drive belts, aerodynamic or hydrodynamic forces, friction or oil whirl, rotor/stator misalignments, defective rotor bars, bent rotor shafts, ets, can be cause mechanical vibrations [4].
Vibration signal involves mechanical signature information about the cause of vibration and through its analysis using different methods, an emerging or developing fault can be detected. When there is fault developing inside rotational machinery, the signature of the collected vibration signal is changing. To be able to measure vibration of a machine, some technical equipment is necessary. In practice, various tools are used, from simple instruments measuring overall vibration to multichannel analyzers equipped with numerous features that facilitate not only the measurement itself but also the analysis of the measured data [5]-[7].
Vibration generated by gears is complicated in its constitution, however it gives many information. To follow the information transferred by vibration one have to be on to a relation between factors having effect to vibration and a vibration signal. In order to detect an approaching failure, a well comprehension of the evidence corresponding to the failure mode and methods of accumulating and evaluating the evidence is needed [5]. Signal processing methods, designing pattern classification methodology and predicting algorithms can be rotating machine fault detection and diagnostics.
The different vibration and acoustic methods, such as vibration measurements in the time and frequency

domains, sound measurements, the shock pulse method and the acoustic emission technique, for monitoring of rolling bearings are presented by Tandon and Nakra [8]-[9]-[10]-[11].

Vibration analysis continues to be the most popular technology employed in rotating equipment. Different sensors are required for different frequencies: position transducers are used for the low-frequency range, velocity sensors in the middle frequency area, accelerometers in the high frequency range and spectral emitted energy sensors for very high frequencies. General types of gear defects such as manufacturing faults (faults of the tooth profile), installation faults (gears' array) and faults, happening while working (teeth's crack) have been defined by Fakhfakh [9]-[13].

Vibration measurement can determine only 60% and 70% faults although it is commonly used in this industry [14].

Gearboxes come under the critical category in many rotating machineries, mainly in chemical industry, aviation, nuclear power stations, automobile, cement, petrochemical, power, paper & pulp, steel and sugar industries etc. The gear drives are the most effective means of transmitting power in machines due to their high degree of reliability and compactness. For reducing or increasing of speeds of transmission systems is used gearbox. These are critical components and as such any failure can prove expensive in both repair cost and down-time. Because they are exposed to wear and fatigue, the gears are damaged prematurely [15].

Any changes in gearbox cause changes in the vibration and thus analysis of vibration signals is proper for monitoring gearbox. Practical experience has shown that this technique in a machine condition monitoring program provides useful reliable information, bringing significant cost benefits to industry. The amplitude and phase alteration on the vibrations of gear is got changed because of imperfections on a gear. Which means any changes in vibration threaten the possible faults [16]-[17].

Most of the non-linear natural facts differentiate the content of frequency. The vibrations of multi-step gearboxes include changing transients, like a short periodical impulsive ingredients generated by strikes among ingredients. Vibration signals produced in gearboxes will comprise three main components, (I) periodic components, (ii) temporary components (iii) wide-band environmental noise. The resources in the gearbox hide the vibration signal in the premature steps of loss and failure initiation and thus it cannot be used for loss detection. Yet, it is definitely at this state that determination of the faults is crucial. Consequently, more influential methods of signal processing are necessary for much better analyse vibration evaluations and more dependable health diagnosis and gearbox condition monitoring [18]. Mechanical faults in shape of impulses forcing periodical pulses onto the main vibration signal are suitable for detection and diagnosis [19].

Li et al. [20] assert that up to two thirds of gearbox faults are because of failures developing in the gears, and about all of these are because of localised imperfections for example fractures generated by fatigue.

The mechanical signals compose of a combination of the main frequency with a narrowband frequency component and the harmonics. Most of these are related to the revolutions of the rotating system because the energy of vibration is enhanced when a mechanical component is damaged or worn. Some of the classic techniques used for fault signals identification contain power spectra in time or frequency domain, and they can ensure an efficient technique for machinery identification on condition that there is the assumption that the signals are constant [21].

Recently, fault identification of industrial gearboxes has received intensive work, and vibration analysis of these machines can determine exact types of faults such as misalignment, unbalance, friction, noise, blade pass, fluctuation, turbulence, etc. Determination of each of these types of faults constitutes in itself a powerful monitoring technique. Some monitoring methods performed to gears are ordinary to use as the scalar descriptors (RMS, Kurtosis, Peak, etc.) and spectral analysis (Fast Fourier Transform, cepstrale analysis, envelope analysis, etc.) [22]-[23].

By measuring and analysing the vibration of a machine, it is possible to detect both the nature and severity of the fault, and thus predict the machine's practical life or failure point [24].

For determination and identification of gear failure is spectral analysis of the vibration signal in the frequency-domain. Because of the most significant condition monitoring elements in the vibration spectra of gears are: the tooth meshing frequency, harmonics and sidebands (due to modulation fact) located on either side of the gear tooth meshing frequency [25].

The most common used techniques for gearbox are such as Faster Fourier Transform (FFT), Time-Frequency analysis, Waveform analysis, Spectral analysis, Order analysis, Time Synchronous Average, and probability density moments.

The use of vibration signals as one of the fundamental tools for monitoring. Many techniques widely used for transmission are such that the time-frequency analysis waveform analysis, Fast Fourier Transform (FFT) spectrum synchronous average, and the cepstrum. Combined time and frequency analysis are progressively used in gear fault identification and are increasingly replacing traditional time-domain and frequency-domain analysis. It's the powerful thing for investigating unstable vibration signals that performing the signal in the time and frequency

domains synchronically and then conclusions can be commented easy [27].

In standard Fourier analysis, for example, a signal processing methods that give local information about both time and frequency. These methods localize signal features in both time and frequency; therefore, these methods have the potential to be more sensitive to early changes in the signal due to impending faults. Many time-frequency (TF) techniques have been performed to the detection of faults in gears [28].

Many time-frequency signal processing methods and the wavelet transforms methods are proper for analysis of vibration signals [18]-[28]-[29]-[30]-[31]-[32]-[33].

## III. VIBRATION TECHNIQUES

Many sort of faults or loss will enhance the machinery vibration levels. These levels of vibration are then transformed to electrical signals for data measuring by accelerometers. As a rule, the information related to the health of the monitored machine is included in this vibration signature. There are some vibration analysis techniques to analyse the bearing vibration [34]. Four categories of vibration techniques are investigated in this work: time domain, frequency domain, time frequency domain and other techniques.

### *A. Time-domain Analysis*

The time domain methods try to analyse the amplitude and phase information of the vibration time signal to detect the fault of gear-rotor-bearing system. One of the simple and cheap fault determination method is time domain analysis of vibration signals. Traditional time-domain analysis are used the amplitude and transient information comprised in the signal of gear vibration time to determine gear faults. Time domain methods are suitable when periodical vibration is observed and failures generate wideband frequencies based on periodic impulses [35]. Although utilization of the waveform allows variance in the vibration signature induced by faults to be detected, t is hard to determine the source of faults [18].

### *B. Frequency (Spectral) Domain Analysis*

The frequency domain methods include Fast Fourier Transform (FFT), Hilbert Transform Method and Power Cepstrum Analysis, etc. They are using the difference of power spectral density of the signal due to the fault of gear and/or bearing to identify the damage of elements. With this method, the vibration signal time domain is turned into its equivalent of frequency. The measured signal spectral content is mostly even more practical than the time-domain to identify gear condition because the complicated time-domain signal can be seperated several frequency components [4]. Its height represents its amplitude and its position represents the frequency. The frequency domain representation of the signal is called the signal. The frequency domain completely defines the vibration. Frequency domain analysis not only detects the faults in rotating machinery but also indicates the cause of the defect. Theoretically, time domain can be converted into frequency domain using the Fourier Transforms and vice versa. It is easy to focus on these frequencies because of importance on them in fault diagnosis. The frequencies of vibrations generated by each component can be approximated for machines worked with known stationary speed. Thus, any variance in vibration level within a particular frequency band can be depended to a particular component. Relative vibration levels' analysis at varied frequency bands can procure some diagnostic information [35]-[36].

### *C. Time-Frequency Approaches*

Audio signals are information rich nonstationary signals that play an important role in our day-to-day communication, perception of environment, and entertainment. Due to its non-stationary nature, time- or frequency-only approaches are inadequate in analysing these signals. Eventually, all methods have some restricts. Also the Fourier Transform (FT), only valid for steady signals, have restricts on its results. A joint time-frequency (TF) approach would be a better choice to efficiently process these signals [37]. In this digital era, compression, intelligent indexing for content-based retrieval, classification, and protection of digital audio content are few of the areas that encapsulate a majority of the audio signal processing applications [38]. Fourier Transform can be utilized for analysis of unstable signals for detection that spectral components be within the signal. In case time information is necessary, using FT will not be proper for the analysis. A number of time frequency analysis methods, like the Short-Time Fourier Transform (STFT), Wigner-Ville Distribution (WVD), and Wavelet Transform (WT), have been introduced. STFT method is used to determine of rolling element bearing failures.

### *D. Time Synchronous Averaging (TSA)*

Processing technique of signal, TSA, extracts periodic waveforms from noisy data. The noise sources and the others, simultaneous with the gear, can be separated from the vibration signature of the gear that makes the TSA is well adapted for gearbox analysis. Further, variations in shaft speed can be verified, such that the dissemination of spectral energy into a contiguous gear mesh bin. To perform this, a signal phased-locked with the shaft's angular position within the system is needed.

Time Synchronous Averaging (TSA) is an essentially different method than the ordinary spectrum averaging which is mostly used in FFT analysis. When the theme is similar, TSA outcomes in a time domain signal with lower noise than would conclude with a single sample. The averaged time signal can be transformed to an FFT. The signal is sampled with a trigger that is

concurred with the signal. The averaging period gradually eliminates random noise because the random noise is not compatible with the trigger. Conventional spectrum based averaging records a data's frame in the time domain, figures out the FFT and adds the FFT spectrum to the averaged spectrum. The time signal is separated and the process is done again until the averaging number is total. If the investigation is about each time record which is utilized to compute the FFT spectra, the signal of interest and random noise will be contained. In that, the averaging is done in the frequency domain, it is not the time domain.

Another important application of time simultaneous averaging is in the waveform analysis of machine vibration, especially in the case of gear drives. In this case, the trigger is derived from a tachometer that provides one pulse per revolution of a gear in the machine. This way, the time samples are synchronized in that they all begin at the same exact point related to the angular position of the gear. After performing a sufficient number of averages, spectrum peaks that are harmonics of the gear rotating speed will remain while nonsynchronous peaks will be averaged out from the spectrum. Two kinds of time synchronous average: time simultaneous linear average and time simultaneous exponential average. Basic of TSA is depending of all vibration to gears will repeat with the rotation of shaft, periodically. The way of improving the vibration, periodic with rotation of shaft, and neutralizing the other components is dividing vibration signal to contiguous parts. Conclusion of this is a signal representing the average vibration for a rotation of shafts [27]. Why this method is utilized is to perform the time-domain of the vibration signal generated by the meshing of the gear teeth over a full revolution [4]-[18]-[39].

*E. Order Analysis*

There are many other techniques that is used to diagnosis of rolling element bearing faults e.g. artificial neural networks (ANNs), fuzzy logic systems etc. According to the non-stationary characteristics of vibration signatures of roller bearing fault, a fault diagnosis method based on empirical mode decomposition (EMD) energy entropy has been presented by Yang et al [40]. Order analysis is a technique for analysing environmental and vibration signals in revolving or reciprocating machinery. Some examples of rotating or reciprocating machinery include aircraft and automotive engines, compressors, turbines, and pumps. Such machinery typically has a variety of mechanical parts such as a shaft, bearing, gearbox, blade, coupling, and belt.

Each mechanical part generates unique noise and vibration patterns as the machine operates. Each mechanical part contributes a unique component to the overall machine noise and vibration. When performing vibration analysis many sound and vibration signal features are related directly with running speed of a motor or machine such as imbalance, misalignment, gear mesh, and bearing defects. Order analysis is a type of analysis geared specifically towards the analysis of rotating machinery and how frequencies change as the rotational speed of the machine changes. Spectral analysis may be inconvenient to determine of gear faults early for gearbox condition monitoring, particularly in local failures, which first influence sidebands in the spectrum.

Some pairs of the gear and other mechanical parts generally promote to the overall vibration. Therefore, it makes very hard to interpret the spacing and progress of sideband relations in a spectrum. It causes the order analysis to be widely used. The vibration signal is resampled from equal time to equal phase increments in the Order Analysis. The angular frequency components in a signal, used with TSA, are included from these outcomes. The equal phase spacing using to resample the signal is designated from a simultaneously recorded reference signal [4]-[18]-[41].

## CONCLUSIONS

This paper listed some of the most traditional features used for machinery diagnostics and prognostics and presented some of the signal processing parameters that impact their sensitivity.

First, the art data processing methods which are generally used in the gear failure determination and identification area that includes frequency domain, time domain, joint time-frequency analysis, time simultaneous averaging and order domain were discussed. After a short theoretical background, the pros and cons of each technique were discussed, a review of applications of the methods that includes the studies made by researchers who carried out these methods to their applications were investigated.

The results from this study have given more understanding on the dependent roles of vibration analysis in predicting and diagnosing machine faults. In the future, we will develop a model of damaged gears in order to numerically investigate to various conditions of operation, defects and feature extraction and fault diagnosis in our study.

## REFERENCES

[1] S.S. Rao, "Mechanical Vibrations," Prentice Hall, 4th edition, March, 2003 Thompson, S. Tribology Solutions: Section 1-Computational Systems Incorporated (CSI), Knoxville, Tennessee, USA. 2000.

[2] S. Devendiran, K. Manivannan, "Vibration Based Condition Monitoring and Fault Diagnosis Technologies For Bearing and Gear Components-A Review," International Journal of Applied Engineering Research, 11 (6), 3966-3975, 2016.

[3] R. Li and D. He, "Rotational Machine Health Monitoring and Fault Detection Using EMD-Based Acoustic Emission Feature

Quantification," IEEE Transactions on Instrumentation and Measurement, Vol. 61, No. 4, pp. 990 – 1001, 2012.
[4] A. Aherwar, S. Khalid, "Vibration analysis techniques for gearbox diagnostics: A Review", International Journal of Advanced Engineering Technology, Vol.III, Issue II, 04-12, April-June, 2012.
[5] I. Yesilyurt, "Gear fault detection and severity assessment using vibration analysis", PHD. Thesis. Manchester: The University of Manchester, 1997.
[6] H. R., Martin, "Detection of gear damage by statistical vibration analysis", Proceeding of the Institute of Mechanical Engineers, Part-C, 395-401,1992.
[7] L. Mitchell et al., "Review of Vibration Analysis Methods for Gearbox Diagnostics and Prognostics", Proc. 54th Meeting of the Society for Machinery Failure Prevention Technology, 1-4, pp. 623-634, May 2000.
[8] Z. Hameed, Y.S. Hong, Y.M. Choa, S.H. Ahn, C.K. Song, "Condition monitoring and fault detection of wind turbines and related algorithms: a review," Renewable and Sustainable Energy Reviews 13:1 e39. 2009.
[9] T.W. Verbruggen, "Wind turbine operation & maintenance based on condition monitoring," WT-O. Final report, ECN-Ce03e047; April 2003.
[10] N. Tandon, B.C. Nakra, "Vibration and acoustic monitoring techniques for the detection of defects in rolling element bearings e a review," Shock and Vibration Digest 24(3):3e11, 1992.
[11] N. Tandon, A. Choudhury, "A review of the vibration and acoustic measurement methods for detection of defects in rolling element bearings," Tribology International; 32(8), 469e80. 1999.
[12] F.R. Stam, "Monitoring & condition-monitoring an wind turbines," 76104-GR-01, January 1998.
[13] T. Fakhfakh, F. Chaari, M. Haddar, "Numerical and experimental analysis of a gear system with teeth defects," Int. J Adv Manuf. Technol., 25:542-550, 2005.
[14] M. Xu, "The State-of-the Art of Machinery Condition Monitoring/Fault Diagnosis Techniques in China and some Development Trends," Proc. first Int. Machinery Monitoring and Diagnostics Conference and Exhibit, Las Vegas, NV, pp. 466-471, September 1989.
[15] G. Dalpiaz, A. Rivola, "Condition monitoring and diagnostics in automatic machines: comparison of vibration analysis techniques," Mechanical Systems and Signal Processing, Vol. 11, pp. 53-73, 1997.
[16] W. Wang, P. McFadden, "Application of Orthogonal Wavelets to Early Detection of Wavelets," Mechanical Systems and Signal Processing, Vol.9, No. 5, pp. 497-507, 1995.
[17] C.J. Stander, P.S. Heyns, W. Schoombie, "Using Vibration Monitoring for Local Fault Detection on Gears Operating Under Fluctuating Load Conditions," Mechanical Systems and Signal Processing, Vol. 16, No. 6, pp. 1005-1024, 2002.
[18] K. Salem Al-Arabi, "Condition Monitoring of Gear Systems Using Vibration Analysis," University of Huddersfield, August 2012.
[19] P. Stevens, D. Hall, E. Smith, "Multidisciplinary Research Approach To Rotorcraft Health And Usage Monitoring," American Helicopter Society 5second Annual Forum, Washington, D. C., pp. 1732-1751, 1996.
[20] C. Li, J. Ma, B. Hwang, "Bearing Localized Defect Detection by Bicoherence Analysis of Vibrations," Journal of Engineering for Industry, Vol. 117, pp. 625-629, 1995.
[21] K. Heidarbeigi, "Adaptive Vibration Condition Monitoring Techniques for Local Tooth Damage in Gearbox," Modern Applied Science Vol. 4, No. 7, pp 104-110, 2010.
[22] Z. Tian, J. M. Zuo, S. Wu, "Crack propagation assessment for spur gears using model based analysis and simulation," Journal of intelligent Manufacturing, Vol. 23, No. 2, 239- 253, April 2012.
[23] R.B. Randall, "Vibration-based condition monitoring: industrial, aerospace and automotive applications," John Wiley & Sons, pp. 289, March 2011.
[24] S. Ebersbach, Z. Peng, N.J. Kessissoglou, "The investigation of the condition and faults of a spur gearbox using vibration and wear debris analysis techniques," Wear, 260,pp. 16–24, 2006.
[25] R.B. Randall, "A New Method of Modelling Gear Faults," ASME Journal of Mechanical Design, Vol. 104, No. 2, pp. 259-267, 1982.
[26] H. Shah, H. Hirani, "Online condition monitoring of spur gears," The International Journal of Condition Monitoring, Vol.4,1, pp1-8, 2014.
[27] W. Wang, P. McFadden, "Early Detection of Gear Failure by Vibration Analysis," I. Calculation of the time-frequency distribution, Mechanical System and Signal Processing, 7(3), 193-203, 1993.
[28] W. Wang, P. McFadden, " Early detection of gear failure by vibration analysis--ii. interpretation of the time-frequency distribution using image processing techniques," Mechanical Systems and Signal Processing, Volume 7, Issue 3, pp.205-215, May 1993.
[29] N. Baydar, A. Ball, F. Gu, "Detection of Gear Failures via Vibration and Acoustic Signals Using Wavelet Transform," Mechanical Systems and Signal Processing, 17(4), pp. 787-804, 2003.
[30] J.H. Lee, J. Kim, H.J. Kim, "Development of Enhanced Wigner-Ville Distribution Function," Mechanical Systems and signal Processing, 15(2), 367-398, 2001.
[31] W.J. Staszweski, G.R. Tomlinson, "Application Of The Wavelet Transform To Fault Detection In A Spur Gear," Mechanical Systems And Signal Processing, Vol. 8, No. 3, pp. 289-307, 1994.
[32] K.C. Sung, H.M. Tai, C.W. Chen, "Locating Defects of a Gear System by the Technique of Wavelet Transform," Mechanism and Machine Theory, Vol. 35, No. 8, pp. 1169-1182, 2000.
[33] Z.K. Peng, F.L. Chu, "Application of Wavelet Transform in Machine Condition Monitoring and Fault Diagnostics: A Review with Bibliography," Mechanical Systems And Signal Processing, Vol. 18, No.2, pp. 199-221, 2004.
[34] S. Patidar, P. K. Soni, "An Overview on Vibration Analysis Techniques for the Diagnosis of Rolling Element Bearing Faults," Int. Journal of Engineering Trends and Technology, Volume 4, Issue 5, pp. 1804-1809, 2013.
[35] B.D. Forrester, "Advanced Vibration Analysis Techniques for Fault Detection and Diagnosis in Geared Transmission Systems," Ph.D. Thesis, Swinburne University of Technology, Australia, 1996.
[36] J. Hedlund, A. Lehtovaara, "Modelling of helical gear contact with tooth deflection," Tribology International, Volume 40, Issue 4, pp. 613-619, 2007.
[37] K. Umapathy, B. Ghoraani, S. Krishnan, "Audio Signal Processing Using Time-Frequency Approaches: Coding, Classification, Fingerprinting, and Watermarking," EURASIP Journal on Advances in Signal Processing, Volume 2010, 28, 2010.
[38] P.D. McFadden, "Window functions for the calculation of the time domain averages of the vibration of the individual planet gears and sun gear in an epicyclic gearbox," Journal of Vibrations and Acoustics 116, 179–187, 1994.
[39] R.M. Stewart, "Some useful analysis techniques for gearbox diagnostics," Technical Report MHM/R/10/77, Machine Health Monitoring Group, Institute of Sound and Vibration Research, University of Southampton, July 1977.
[40] Y. Yang, Y.Dejie, C. Junsheng, "A roller bearing fault diagnosis method based on EMD energy entropy and ANN," Journal of Sound and Vibration, Vol. 294, pp. 269- 277, 2006.
[41] K.R. Fyfe, E.D.S. Munck, "Analysis of computed order tracking," Mechanical Systems and Signal Processing, 11, (2):187-205, 1997.

★★★