Condition Monitoring of Straight Bevel Gear using Vibration Techniques

A Dissertation submitted by

Shah Jital (11012508)

to

Department of Mechanical Engineering

In partial fulfilment of the Requirement for the

Award of the Degree of

Master of Technology (Machine Design)

Under the guidance of

Hitesh Dhingra

May 2015

CERTIFICATE

This is to certify that Mr. Jital Shah has completed M.Tech dissertation titled "Condition Monitoring of Straight Bevel Gear using Vibration Techniques" under my guidance and supervision. To the best of my knowledge, the present work is the result of his original investigation and study. No part of the dissertation has ever been submitted for any other degree or diploma.

The dissertation is fit for the submission and the partial fulfillment of the conditions for the award of M.Tech Mechanical Engineering.

Date: Signature of Advisor

Name:

DECLARATION

I hereby declare that the dissertation entitled, "Condition Monitoring of Straight Bevel Gear using Vibration Techniques" submitted for the M.Tech Degree is entirely my original work and all ideas and references have been duly acknowledged. It does not contain any work for the award of any other degree or diploma.

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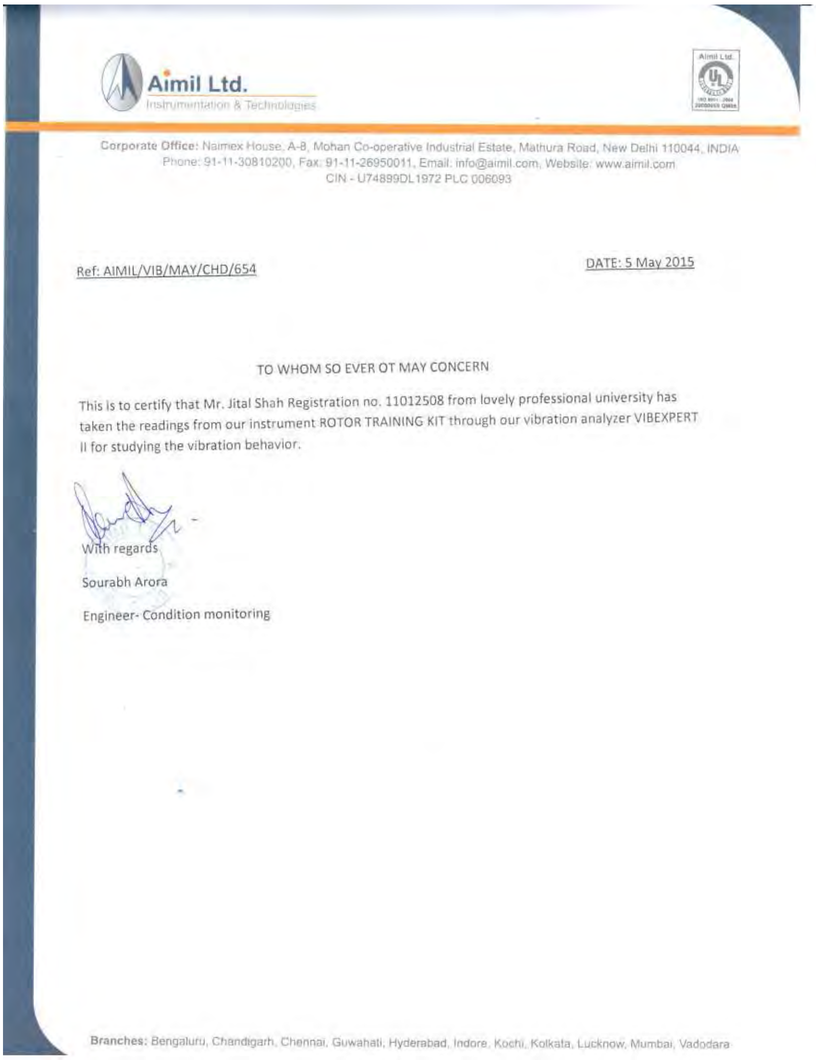

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Instrumentation & Technologies

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This is to certify that Mr. Jital Shah Registration no. 11012508 from lovely professional university has taken the readings from our instrument ROTOR TRAINING KIT through our vibration analyzer VIBEXPERT II for studying the vibration behavior.

With regards

Sourabh Arora

Engineer- Condition monitoring

Branches: Bengaluru, Chandigarh, Chennai, Guwahati, Hyderabad, Indore, Kochi, Kolkata, Lucknow, Mumbai, Vadodara

ACKNOWLEDGEMENT

One of benifit of having completed my M.Tech thesis is an opportunity to acknowledge and thanks the people who have contributed their help for the study. Firstly I am highly grateful to the almighty who provided me such a great opportunity to work on such an interesting and knowledgeable topic. I want to express my deep gratitude and respects to my guide Er. Hitesh Dhingra for his valuable guidance, constructive criticism, patience and constant encouragement throughout my M.Tech program. I am extremely thankful to our head of department Dr. Rajiv Sharma, whose excellent leadership and administration made this research possible. I am also thankful to other distinguished faculty of Mechanical Department, LPU for their support whenever needed.

I am indebted and would like to express a deep sense of gratitude to Dr. Sukhjeet Singh, GNDU Regional Campus, Sathiala for their precious time, loyal support, invaluable guidance, and attitude for encouragement during the experimental work. I appreciate the freedom provided by him for gaining a practical knowledge on the system. All the required equipment as well as knowledge were provided as well as well-explained during experimentation. My regard are with Mr. Vinod, for providing me Gearbox in the given period of time,with absence of error for the experimentation. I am also thankful to Er. Aman Verma and all employees of "Central Institute of Hand Tools (CIHT)", Jalandhar for their support during experimental work.

Last but not the least, I would like to thank my parents, and family for always being there when I needed them most and for their moral support motivating me at every step that kept my spirit up during the endeavor.

Place: Lovely Professional University, Phagwara
Date: May 7, 2015 Shah Jital

ABSTRACT

Bevel gear system have various major application in industries. Faulty gear systems affect the working of the system and they result in damage of adjacent parts. Sudden shutdown of machine is not desirable in today's competitive world. Fault diagnosis helps in early detection of developing faults and thus increases the reliability of the system. Vibration signal of the system is a sensitive parameter to the type and severity of faults. Thus, vibration analysis can be an effective tool to study a dynamic behavior of the system. Condition monitoring is a tool that helps a user in prediction the health level of system. It includes various signal processing techniques that can extract the useful information from the raw vibration signal of system without any losses. This condition monitoring tools are computationally inexpensive, less time consuming and highly accurate in analyzing the signals. But it too has a big disadvantage that different techniques give different results for same fault. So, it is also necessary to select a suitable signal processing to obtain accurate information from signals containing noise.

The present work outlines the vibration analysis of a single stage straight bevel gearbox in which a seeded fault (i.e. one broken tooth) is introduced in one of the gears. Vibration signatures in form of time domain are acquired by the accelerometer at different speeds. EMD (Empirical mode decomposition) is applied to gear fault diagnosis for the fault detection.

EMD could exactly decompose the fault signals into a number of intrinsic mode functions (IMFs), from which the frequency families could be separated effectively. Furthermore, when faults occur in gear, the average energy, total energy and average power of the gear vibration signal would change correspondingly. Thus, the fault information of the gear vibration signal can be extracted effectively from the various energies and power of the signal calculated. The analysis results from the experimental signals show that both frequency family separation method based on EMD could extract the characteristics information of the gear fault vibration signal effectively.

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Place: Lovely Professiona University, Phagwara | Shah Jital
Date: May 7, 2015 | (11012508)

ABBREVIATIONS

Abbreviations	Description
DAQ	Data Aquistion
EDM	Electrical Discharge Machine
EMD	Empirical Mode Decomposition
FFT	Fast Fourier Transform
GMF	Gear Mesh Frequency
IEPE	Integrated Electronic Piezo Electric
IMF	Intrinsic Mode Function
RMS	Root Mean Square
TSA	Time Syncronous Average
VFD	Variable Frequency Drive

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CHAPTER 1

INTRODUCTION

1.1 Overview

Bevel Gears have their application in fields of automobiles, mining equipment, cooling tower, robotic applications, railway equipment, military applications, and chemical plants [3]. The basic application of bevel gear is to transmit power between intersecting or non-intersecting shafts which are at some angle between $0°$ to $180°$ with respect to one another. The face of the bevel gears on which gear tooth are made is conical in shape and when the surface is extended inwards it intersect at a single point along the shaft known as vertex of the gear [7]. A gear system dissipate the energy in form of vibration and heat which result in less output. These vibrations get increased with changing fault conditions of the system. But the industrial applications need an efficient machine which have longer lifespan to perform its task to meet the production and market needs. Thus, condition monitoring of machines was developed and is widely used in industry.

Condition monitoring indicates significant change in certain parameters because of faults which gets developed in the system with passage of time. These analyzed parameters are closely related to the dynamic behavior of parts of the system and are sensitive to various faults and their level of severity. The parameters also help to analyze the present health level of the system, thus providing an alarm to the user to take preventive steps for the unseen large failures in machine. Some of condition monitoring techniques are: vibration analysis, lubricant analysis, acoustic emission, infrared thermography, and motor current Signature analysis (MCSA).

Rotating equipment have vibration/noise induced into them because of different working criteria like high speed, larger loads, less space and lighter weight. The industries have a large number of parameters to analyze and control the accuracy. For rotating machines, vibration and noise are the dominating parameters which affect the working of the system. Vibration analysis proves itself as an simple and efficient tool to study the condition of system as it needs simple setup as well as the calculations are done effectively in short time durations.

Faults in the rotating system result because of starting torque, manufacturing error, bearing failures, gear misalignment, unexpected load, resonance vibration and few others. The commonly observed faults in a bearing system are shaft misalignment, inner race faults, outer race faults, cage faults, and balls faults, while in gearbox system are crack, pitting, tooth breakage, scuffing, wear and scoring.

Detection of faults at early stages prevents sudden shutdown of the system and can inform to take preventive steps to reduce effect of the faults on the other parts of the machine. Faults have their own characteristics and show different vibration signatures. These specific vibration signature can help to analyze the condition of system and detect the faults accurately.

1.2 Scope of the study

With advancement in the machinery, industries need effective, and durable machines capable of giving high production rates. Sudden shutdown in system and maintenance time required for machine will result in increase of economic loss as production rate reduces. Therefore, the condition monitoring of the system has become a basic need for large industries to keep up with the market without facing great loss in economy as well as fame.

Some of industrial needs of development in condition monitoring are:

(a) Prediction of equipment failure

(b) To have a holistic view regarding condition of equipment

(c) Achieve a great accuracy in prediction of failures

(d) Reducing cost of condition monitoring

(e) Improving and increasing reliability of the equipment

(f) Optimizing the performance of equipment.

Vibration or noise signals induced in a system contain information regarding the condition as well as dynamic behavior of the system. Condition monitoring tools help to analyze the signals and also to retain such information from the signals for different type of faults and health level in the machine. From the various tools mentioned in Section 1.1, vibration analysis has its applications in many fields as it is easy to apply and can provide accurate data regarding the condition of the system.

1.3 Research Objectives

Present research work deals with the diagnosis of Straight Bevel Gearbox condition by doing planned experiments and using a signal processing technique which can effectively detect and extract the fault features of the healthy and faulty gear system.

The system of rotating bodies have induced signals which contain data regarding health level and faults present in the system. These signals have a specific value of frequency, amplitude, and phase for different faults, severity of faults and position of fault respectively. With increase in characteristics (occurrence and severity) of fault, the characteristics (frequency and amplitude) of signals also increases. Thus, one aim of this thesis is to acquire accurate data from the experiment for healthy and faulty system.

Condition monitoring tools and techniques of signal processing are easy to implement and computationally inexpensive. Signal processing techniques have their application for on-line condition monitoring and detection of faults in automated system. Signal processing helps in analyzing and comparing the signals of healthy with faulty systems. Thus, second objective of this thesis work is to utilize an appropriate signal processing technique that can detect a common fault in gearbox for a set of signals obtained from same fault in the gear system. Matlab software is used for analyzing the data in the present study.

1.4 Orientation

Present study has been classified into six chapters as discussed in the next few lines.

Chapter 1 presents “Introduction“ to the study which includes “Overview“, “Scope of the study“ and “Objectives“ regarding the experimentation work.

Chapter 2 has detailed “Introduction to Straight Bevel Gears“, “Different Faults in the Gears“, and “Related Literature Review“, which also considers review of work presented on gearbox monitoring in past years along with motivation attained to work on detecting faults of straight bevel gearbox and also about various tools helpful in diagnosis.

Chapter 3 presents “Experimental methodology“ which covers setup along with methodology (procedure) and measurement instruments used for obtaining signals induced in the system.

Chapter 4 discusses about the “Signal Processing Techniques“ that can be used for analyzing the signals along with limitations and advantages. Thus, deciding an appropriate technique to conduct the further analysis for reaching a beneficial result.

Chapter 5 presents the “Results“ that are obtained from the experimentation in form of vibration signals and processing done further to identify the faults.

Lastly Chapter 6 talks about “Conclusion and Future Scope“ about the study conducted.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction to Bevel Gear

Gear system is one of an important rotating component which has its application in field of power transmission from one shaft to another. Many industries have application of gear system in automobiles, mining equipment, cooling tower, robotic applications, railway equipment, military applications, and chemical plants [3]. Failure in a gear system may result a disaster in whole system and will stop the complete process of production resulting in great economic loss. Thus, it has become necessary to monitor the condition of gears while they are under loading. In this chapter, basics of bevel gear, different faults that can be observed and a review regarding literature on "Analysis of gear system" presented in different papers has been discussed.

Bevel gear system has its application when power transmission is between two intersecting or non-intersecting shafts that are having some angle between $0°$ to $180°$ between them. William Gleason was the person who invented the first bevel gear planer [1]. As the bevel gear transmit power at some angle, tooth faces are conical in shape for proper meshing of tooth. This faces when extended inward they coincide with the axis at an imaginary point known as vertex of the cone. The imaginary vertices of both gears must coincide at a point for effective power transmission. An industrial application of Bevel Gear system for transmitting power from horizontal shaft to vertical shaft with reduction in speed is shown in Figure 2.1(a).

(a) Bevel Gear used in Industrial applications [7] (b) Straight Bevel Gear System [8]

Figure 2.1: Types of bevel gears

There are two important terms related to gears, which are pitch surface and pitch angle. Pitch surface is imaginary toothless surface of gear obtained by averaging the teeth of gear and pitch angle is angle of pitch surface to axis of gear. Almost of bevel gears are having pitch angle 90° of angles between shafts. The gears with pitch angle having less than 90° are called external bevel gears because teeth are pointing outwards, while gears with pitch angle more than 90° are called internal bevel gears. The gear with exact 90° pitch angle and teeth pointing outward are called crown gear.

In most of applications straight (spur) bevel gears are used. So developing fault diagnosis techniques for analysis of spur bevel gear is an important field. Some of applications are railway equipment, robotic applications, machine tools, textile machines, cooling tower, automobiles, and mining equipment.

2.2 Types of Bevel Gears

In recent times, application of gears have been advanced in industries. Due to their different applications, they can be classified as: spur gear, bevel gear, helical gear and worm gear. As we have discussed above, bevel gear transmits power at an angle. It is further classified in four categories, which are straight, spiral, zerol and hypoid bevel gears. They are discussed below:

2.2.1 Straight Bevel Gear

Straight Bevel Gears are the bevel gears of simplest form. The pitch surface is conical but the teeth are straight and tapered when observed from normal view to pitch surface. The teeth when extended inward would pass through a common intersection point on the axes. A straight bevel gear setup (Figure 2.1(b)) that is used for power transmission in two perpendicular shafts is presented.

2.2.2 Spiral Bevel Gear

Spiral Bevel Gears are having teeth which are curved and oblique with respect to the axes of the shaft. During meshing, the contact begins from one end of tooth and progresses to the other. Spiral bevel gear system (Figure 2.2(a)) can be arranged as below:

(a) Spiral Bevel Gear System [9] (b) Zerol Bevel Gear System

Figure 2.2: Spiral bevel and zerol bevel gears

2.2.3 Zerol Bevel Gear

Zero Bevel Gears are having straight teeth which are curved as spiral bevel gear. Zerol Bevel Gear system (Figure 2.2(b)) manufactured by various industries.

2.2.4 Hypoid Bevel Gear

Hypoid Bevel Gears are similar to spiral bevel gear but the pitch surface are hyperbolic and not conical. Pinion can be above or below the gear center allowing larger diameter of pinion which result in longer life and smooth mesh. Gear system of Hypoid Bevel Gear is shown in Figure 2.3.

Figure 2.3: Hypoid Bevel Gear System [4]

2.3 Different Faults in Gear systems

During working condition, gears are in contact with other component like shafts, motors, meshing gear, etc. Due to this components, the gears under load and a stress is generated internally in the gear system. Also the loading causes the rubbing in tooth of gears which result in wear, friction, sudden impacts on gear system, which may result in form of faults in the system. This section will provide an over-view on different faults observed along with their characteristics and effects. Common causes of faults are mentioned below:

a) Load more than theoretically permissible value

b) Larger torque

c) Improper Material selection

d) Errors related to manufacturing processes

e) Misalignment in system

2.3.1 Excessive Wear

Wear is one of the commonly observed faults in the gear tooth because is a surface phenomenon of removal of metal layer uniformly or non-uniformly at the contacting surface of the gear teeth. There are many types of wears that can be observed in the gear system which are discusses as below:

2.3.1.1 Abrasive Wear

The wear in material due to rubbing of two metals in contact is called abrasive wear. The wear observed in the system due to such metal contact results in radial scratch on tooth surface, signs of finish of laps and some other indications which confirms for the wear of the gear.

2.3.1.2 Impact Wear

The phenomenon of removal of metal due to impact of external material which is bombarded on the surface under study is called impact wear. The material that is bombarded acts as an external force which makes the layer of surface of the specimen to wear out and to result in form of rough surface at the point of contact.

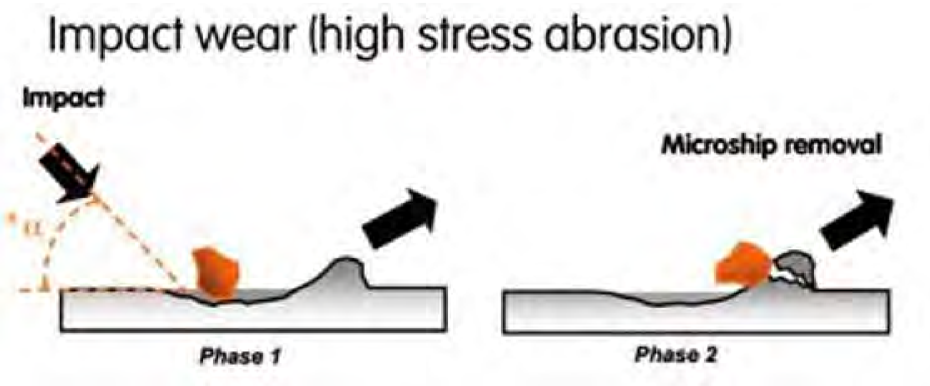


Figure 2.4: Impact Wear [5]

2.3.1.3 Corrosive Wear

The wear which occurs due to reaction of metal with chemical or highly reactive fluids which are present in the surrounding of the system is termed as corrosive wear. It can be caused due to air, lubricant, coolant, or any fluid which can react with the metal surface to corrode. This layer is then easy removed when it comes in contact with another layer which has relative motion with respect to this layer.

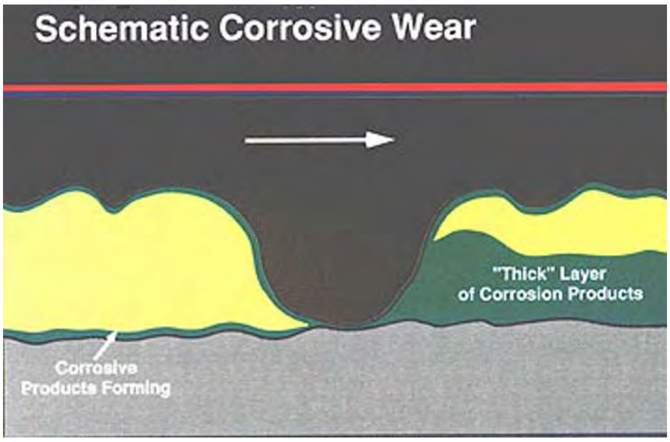


Figure 2.5: Corrosive Wear [6]

2.3.2 Pitting (Surface fatigue)

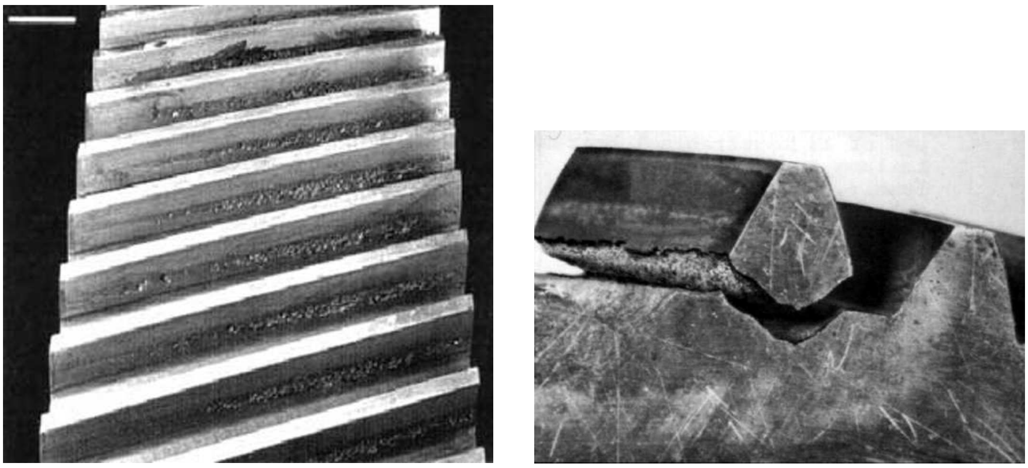
Pitting can be defined as failure due to surface fatigue caused by continuous surface (contact) stresses and number of cycle also affects it. It can be characterized by removal of material and formation of cavities. It can be further classified as:

2.3.2.1 Initial Pitting

Improper fitting or conforming of gear-tooth can cause initial pitting. It is explained as pit formation of diameter 1/64 to 1/32 inches in diameter, where over-stressed areas are observed. It results in redistributed loading, as material from highly stressed areas is removed. Commonly observed cause of such problem is misalignment across the face width of gear.

2.3.2.2 Destructive Pitting

Predominant pitting in dedundum and some addendum regions is termed as destructive pitting. The pits generated are larger in diameter than initial pitting. The major cause of such pitting is overload which cannot be distributed by initial pitting and will occur until the tooth profile is destroyed completely.



(a) Piting (Surface Fatigue) (b) Complete Tooth Breakage [10]

Figure 2.6: Gear faults

2.3.3 Teeth Breakage/ Fractures

Fracture or breakage of tooth in gear is caused by cyclic bending stress beyond endurance limit on the tooth. This stresses result from: poor design, overload applied while working, misalignment of shafts and defects located on tooth surface. It can result in complete or partial tooth breakage which are shown in Figure 2.6(a) and 2.6(b) respectively.

Figure 2.7: Partial Tooth breakage

Tooth breakage can be classified in two categories depending on their causes as:
a) Fatigue breakage/crack,
b) Overload breakage and
c) Random breakage.

2.3.4 Fatigue breakage

Fatigue bending stress results in a crack formation at the root of the tooth which propagates and causes complete or partial tooth breakage. It is a result of Hertzian contact stresses generated due to meshing of gears. A sign of fretting and conventional smooth beach marks are observed along with a focal point of fracture. The final position of tooth breakage leaves a rough jagged appearance. Fatigue breakage can be avoided by considering materials with higher strength or proper design of tooth so that the load is uniformly distributed all over the tooth face. Also full fillet gear surface at root can be efficient.

2.3.5 Scoring(Scuffing)

While excessive load is acting on a gear system, if the lubricating oil film gets ruptured then there is adhesive wear between two gears tooth in mesh resulting in the

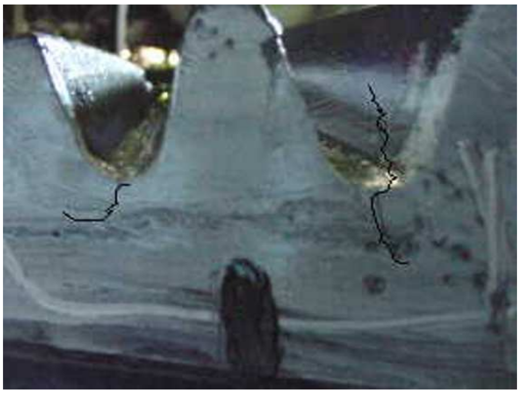


Figure 2.8: Fatigue breakage in gear tooth

Scoring/scuffing fault. It can be characterized by metal transfer from one tooth to another. Major causes of scoring can be design error, misalignment and assembly error. Preventive steps include increasing viscosity of oil, reduction in load or smoothening of rough area. Scuffing can be mild which is not progressive and so doesnt constitute a primary failure or severe which occurs on gear tooth. It can be further categorized as a) Frosting (initial stages), b) Moderate scoring (throughout addendum/ dedundum), c) Destructive scoring (tear/wear marks) and d) Localized Scoring (localized areas).

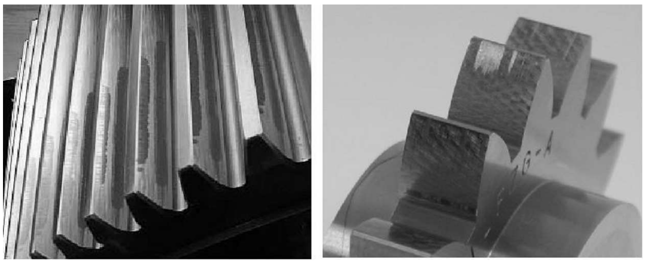


Figure 2.9: Scuffing in Gears (due to adhesive wear)

2.3.6 Plastic Flow

Surface deformation in surface or subsurface of gear tooth due to high contact stress and sliding of tooth in mesh result in plastic flow. Softer materials shows plastic flow more often but it can also be observed in harder materials. During meshing the surface of softer material gets pushed in the direction of sliding which result in battered or dent appearance of deformed shape. This fault can also be observed due to manufacturing error or combination of wear and cold working of system. Plastic flow wear can be corrected only by replacement of gearbox. But of plastic flow can be eliminated by reducing contact stresses and increasing hardness of contacting surface material. It can be categorized on basis of direction of plastic flow of material as a) Cold flow, and b) Ridges.

Figure 2.10: Plastic Flow in Gear

2.4 Relevant literature related to Condition monitoring of gears

Gear under meshing condition is the important behavior which should be understood before monitoring the gear system. Research studies about the basic understanding of the gear meshing and faults occurring because of this are available in the previous studies by various authors.

For the better understanding of the gear related faults occurring in the gearboxes, a number of mathematical and experimental studies have been made in the past by researchers. A number of mathematical models have been proposed by various researchers in the literature [17, 21]. Tuplin gave the first vibratory model for gear dynamics in 1950.

Belsak and Flasker [12] gave an introductory research for monitoring condition of gear units using vibration techniques.

Capdessus et al. [13] introduced the theory of cyclo-stationary process to be a powerful tool that can be used for diagnosis of rotating machinery.

A paper published by Sadeghi et al. [22] on fault detection and identification for gearbox system using neural networks showed that 2-layered perceptron Neural Network method is an effective method of diagnosing faults in gear and bearing systems. A new method was also developed by Dong et al. [16] in his studies for fault detection of rolling element bearing with help of Modified Morphological method. The results showed that this proposed method was an effective tool to detect faults in system having large amount of noise.

A technique used for vibration based fault diagnosis of Straight Bevel Gear using Fuzzy technique in one of the works's [23]. It included knowledge of decision tree for an appropriate technique selection. The result showed that Fuzzy technique can be an alternative method which is effective in fault diagnosis. In Later stages, Li [19] showed that Dual tree complex wavelet transform used for bearing fault diagnosis reduces the spectral aliasing and can effectively detect faults.

A paper on gear fault diagnosis with help of Hilbert spectrum based on MODWPT and comparison with EMD approach was presented by [25] in which a new approach was used for analyzing the signal using instantaneous amplitude and frequency. This was processed by Maximum Overlap Discrete Wavelet Packet Transform (MODWPT) and a spectrum was obtained by Hilbert Spectrum by Hilbert Haung Transform. This approach was compared with a well developed Empirical Mode Decomposition (EMD) approach to make it sure that the new proposed approach was an effective method for fault diagnosis of gear system. Results showed that MODWPT has perfect time- frequency resolution and gives user excellent results.

A methodology was presented by A. Saxena [24] for analyzing vibration data which were obtained from planetary Gearbox system with help of Complex Morlet Wavelet. In this paper it also proposed that the z-test can be used for evaluating the relative performance of features of the faults. Results were positive for this new proposed method and showed that by z-test the Frobenious Norm of Wavelet Map was best for feature presentations.

Bartelmus [11] presented a novel approach for monitoring the condition for a gearbox with non-stationary operating conditions. In this paper, they studied planetary gearbox along the condition of varying external load. The approach made a simple regression between classical spectral based features and operating condition indicator which have linear relation. Instantaneous speed at input is an indicator for the operating condition feature while sum of vibration meshing components is indication for diagnostic features.

A robust diagnostic model was represented for gearbox which is subjected to vibration monitoring by [27]. In this gear faults were studied under varying load conditions. It showed that Gear motion residual signals which is obtained by removal process of harmonics of gear mesh frequency from time synchronous average (TSA) is load independent and can detect faults at early stages than conventional and newly proposed methods.

A new approach called Parks vector approach was presented by [26] for Bearing Fault detection in which 3 phase stator current analysis was conducted for induction motors. According to this 3 phase stator current analysis, sum of current in stator is zero under balanced condition. Parks vector which is function of phase variable can be used to get parks vector components. Results showed that it was a powerful and General approach with superiority to conventional methods.

An advanced methodology was proposed by [15] for automated time synchronous averaging of gearbox without speed sensors mounted on system. In this method the approximate speed of system should be known. Previously harmonics were selected on trial basis, so it was proposed to calculate low signal to noise ratio related to gear mesh harmonics and to deduce low passing filtering effect on TSA which can predict approximate harmonic values. Results shows this methodology to be more effective for system where speed cannot be determined by any other method.

Application of frequency family separation method was used on Gear fault diagnosis based on Empirical Mode Decomposition (EMD) and local Hilbert energy spectrum represented by [14]. Results showed that combination of EMD and Hilbert energy spectrum can be used for fault detection in the gear system. In this method, EMD decomposes the vibration signal into various intrinsic mode functions and Hilbert energy spectrum distributes the energy of signal. As vibration signal changes with different faults, this combination can be helpful in detecting faults in the gear system.

New method that has also been used for analyzing gear unit is presented in Analysis of Vibration and Noise for determining Condition of Gear Unit. In this method, the noise signals are obtained using mic system at various sources of noise. This signal was represented by Qian improved Adaptive Transform for crack in pinions tooth. Results showed Acoustic Source Visualization is more appropriate and reliable than Acoustic Emission.

A Hermitian Wavelet Transform was used for diagnosis of gear crack fault under run-up condition by [20]. This paper showed that method based on combination of Order-tracking method and Hermitian wavelet based amplitude and phase map can be effectively used when crack is slightly observed and it detection becomes necessary.

2.5 Problem Statement

After a comparative and detailed study of different condition monitoring techniques specially in signal processing carried in the literature review, which shows a scarcity of literature on the condition monitoring of straight bevel gearboxes. Another conclusion that can be stated is that time-domain cannot describe the gearbox condition in early stages. Spectral analysis cannot give information on time of a particular frequency component. Moreover it cannot be used for non-stationary signals. In the present study, it is proposed to use empirical mode decomposition (EMD) method for extracting the fault information from the signals of healthy and faulty straight bevel gears. Intrinsic mode decompositions (IMF's) associated with Empirical mode decomposition have been used to show the comparison between the healthy and faulty running gearboxes. Average power, total energy and average energies associated with the imf's of the various signals have been calculated to show the difference between the healthy and faulty gears. The motivation of the study is that EMD method and the various energies associated with these have not been explored much for straight bevel gear.

CHAPTER 3

EXPERIMENTAL METHODOLOGY

This chapter deals with a detailed information of the experimentation carried for Fault Diagnosis of Straight Bevel Gearbox using Signal Processing Techniques. A detailed information of working condition, specification of faults and procedure for experimentation is provided along with the designing of the setup for the experiment. Equipment used for experimentation like motor, gearbox, data acquisition system, and other mountings are also discussed to provide their specifications and use in the experimental rig.

3.1 Experimental Setup

In the presented study, the test rig provides a deep understanding about vibration signature induced in the system because of different faults developed in machine and their level of severity. This section is further divided in subsections as follows:

1 Support system

2 Motor and its controlling system

3 Test gearbox

4 Data Acquisition System

3.1.1 Support System

As discussed in section 1.3, the first aim of this study is to design an experimental setup, which helps to obtain repeated as well as accurate signals for the study. Taking various aspects of vibration, material properties and requirements a test rig is modelled and designed using CAD software like AutoCAD (2D modelling) and SolidWorks (3D modelling). Some important components modelled are discussed below:

3.1.1.1 Base plate

The base plate is an important component of test rig as it separates the test system from the surrounding. Thus an accurate vibration signals of the system are obtained for healthy and faulty systems without effect of surroundings. Base plate is made from mild steel of size $36x16x1.25''$ and its model is shown in Figure 3.1.

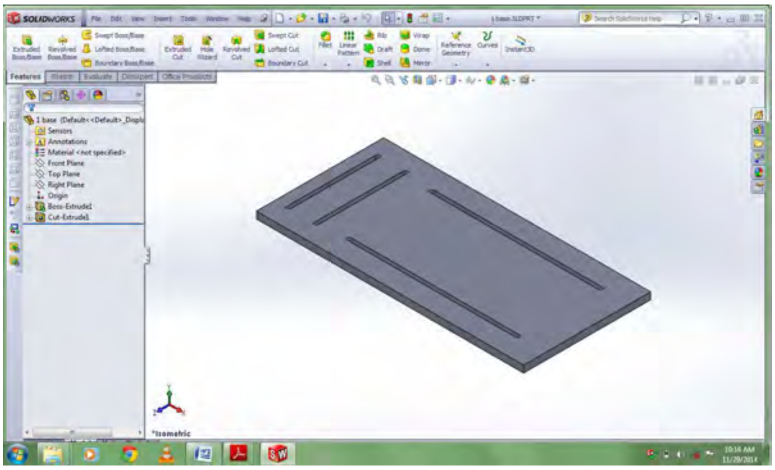


Figure 3.1: CAD model of Base Plate

3.1.1.2 Movable plate

The plate which is mounted above the base plate and is a part of gearbox mounting is named as movable plate. Its purpose is to adjust and allow a specific distance between gearbox shaft and motor shaft for proper mating. A model for movable plate is shown in Figure 3.2.

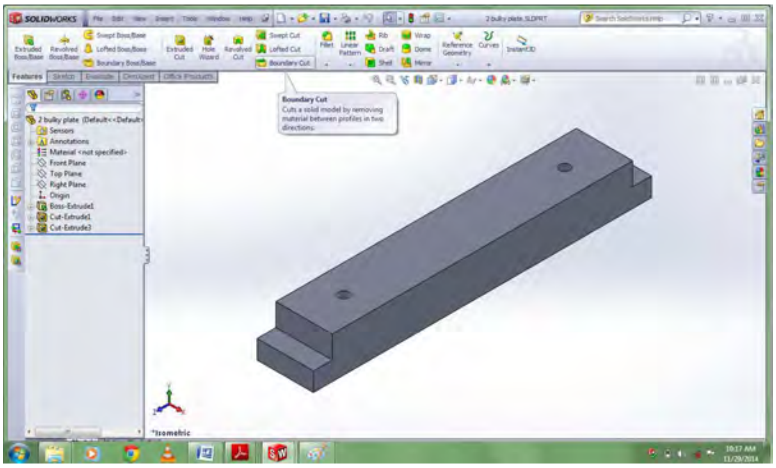


Figure 3.2: CAD model of Movable plate

3.1.1.3 Gearbox support plate

On top of this movable plate, a gearbox plate is arranged to provide support and fixture to gearbox during testing. Its aim is to provide lateral movement to the gearbox for proper alignment of the gear and motor shaft in horizontal direction. Model for this gearbox plate can be shown as in Figure 3.3.

The dimension for the above designed parts were provided to Central Institute of Hand Tools, Jalandhar, where these parts were processed and manufactured. Thus, process of designing of setup was successfully completed and the finally processed parts were precise within accuracy of 5 micronmeter as per the requirement.

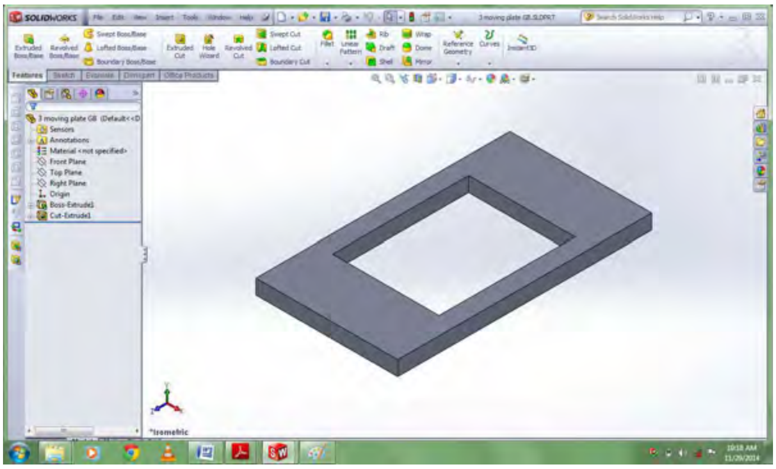


Figure 3.3: CAD model for Gear Box plate

3.1.2 Motor and its mounting components

An A.C motor is used to drive the gearbox under testing during experimentation. The operating speed required during experiment is ranging between 0 hz to 60 hz (i.e. 0-3600 rpm) for conducting the study at different frequencies. So, a variable frequency drive (VFD) system of Delta Electronics Inc. is attached before 3 phase induction motor to control the input frequency of current flowing. Specification of motor used for providing power to the test gearbox is given in Table 3.1.

Table 3.1: Specifications of induction motor

Make	Number of phases	Power	Operating voltage / Current rating	Operating frequency	Nominal operational speed
ABB	3	1 H.P	240 Volts / 1.6 A.	50 Hz	2840 r.p.m

The shaft of motor is connected to the shaft of gearbox with help of a coupling which provides a flexible movement to both the shaft to optimize the alignment between both the shafts. A reverse dial gauge indicator was used for alignment of the shaft with tolerance of 5 microns. The horizontal as well as vertical alignment were achieved within 20 micronmeter with help of screw and shims respectively. Reverse dial indicator used in the experimentation is shown in Figure 3.4.

Figure 3.4: Picture of reverse dial indicator

3.1.3 Specifications of Gearbox

A gearbox used in the experimentation has been manufactured by Gear India pvt. Ltd., Baroda, Gujarat. The dimension of the gearbox are 214 X 186 mm (outer peripheral) and average thickness of the gearbox walls is 14 mm. The detailed specifications of gearbox are given in Table 3.2:

Table 3.2: Straight bevel gear specifications

Design Parameter of Bevel Gears	Pinion	Crown
Number of Teeth	18	36
Module (mm)	2	
Material	EN-353	

The test rig manufactured has either option to choose one shaft as input and another as output without considering the gear ratio. But as in most of industries smaller gear is considered as pinion and the speed of output shaft is less than the input. So, in this experimentation also we have considered 18 teeth of pinion gear as input shaft and 36 teeth gear as output shaft providing speed reduction of 1:2 ratio. The gear tooth were cut using a shaper machine.

3.1.4 Data acquisition system

3.1.4.1 VIBXPERT

A dual channel, portable hand held vibration monitoring instrument was used with piezoelectric accelerometers for monitoring the engine vibrations (Make- Pruftechnik; Model- VIBXPERT Data collector and FFT analyzer). It is a high performance, full-featured FFT data collector and signal analyzer and collects field data including vibration information, etc.

3.1.4.2 Accelerometer

Changes in acceleration forces are measured by an accelerometer which is an electromechanical and it provides an output in form of signals. This acceleration forces which are measured can be static or dynamic in nature. A vibration produced in a system is a dynamic force that helps in prediction on type of motion that the system follows [2].

A piezoelectric accelerometer (PCB 608A11) selected for the study is shown in the Figure 3.5. It has large dynamic range along with high mounted resonance frequency and its sensitivity is 10.2mV (m/s^2). This accelerometer was mounted above the top plate of straight bevel gearbox system which can help in obtaining the vibration signal of system containing information regarding health of gearbox. It has design made up of stainless steel and also has hermetic sealing which withstands chemical contamination allowing installation in some of submerged regions. The accelerometer and data acquisition system are connected using an integral cable. Signals generated in accelerometer can be obtained in controlling/host computer using coaxial Bayonet Neill Concelman (BNC) cables.

This BNC cable consist of radio frequency (RF) connecter used as coaxial cable with a miniature quick connect/disconnect. By applying a quarter turn in the coupling nut, mating of accelerometer can be done with the gearbox. A mounting of steel material was being screwed to mount the accelerometer in direction along the line of action of the gear. The accelerometer (PCB 608A11) specifications are mentioned in Table 3.3.

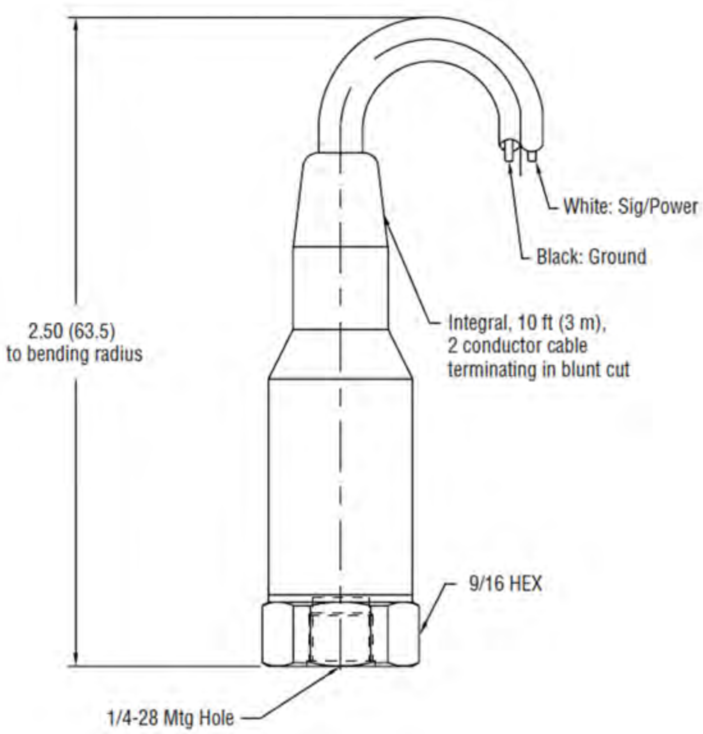


Figure 3.5: Accelerometer 608A11

Table 3.3: Specification of accelerometer 608A11

Sensitivity (± 20)	10.2 mV(m/s^2)
Measurement range	± 490 m/s^2
Frequency Range (± 3 dB)	0.5 to 10,000 Hz
Resonant Frequency	22 kHz
Broadband Resolution (1 to 10,000 Hz)	3434 mm/s^2
Non-Linearity	± 1%
Transverse Sensitivity	$\leq \pm$ 7
Sensitivity (± 20 %)	10.2 mV(m/s^2)
Size (hex x height)	9/16 in x 16 mm
Weight (with cable)	99.3 gm
Mounting thread	1/4-28 Female
Housing material	Stainless steel
Cable length	3m
Cable type	Polyurethane
Overload limit (shock)	49,050 m/s^2 pk
Temperature range	−54 to +121°C

Lab View was used as a user-friendly bridge between hardware and user. This software allows user to store some of custom modules and controlling of data acquisition in detail. Matlab R2010a (student version) was used to import the data from Lab View for analyzing the signals and applying signal processing techniques to extract the information enclosed in the signals besides presenting the results.

3.2 Experimental procedure

A gear box test methodology was developed and it has been discussed below:
1. Prior to actual testing of the gearbox, it was made to run for six-eight hours daily for two days. This was necessary to remove contamination in gearbox resulting from manufacturing process.
2. Also, during the assembly process, dirt was ingested and debris was generated due to threading, joining, welding, etc. The contamination in form of sludge and wear metals, were seen present in the drained oil.
3. The gearbox was then properly washed with kerosene oil and cleaned before starting the testing process. After this, the gearbox was run for approximately 15 minutes to permit the gear oil and bearing grease to warm up towards reaching normal operating temperatures for steady state operating condition.
4. In the first stage of test, a healthy gearbox was run at 10 Hz and data was captured during this phase of testing to establish a baseline that could be used for comparison and analysis against a gearbox with a fault seeded into it. The speed was then incremented by 10 Hz for each recording until a maximum operational speed of 60 Hz was reached.
5. In the second test stage, the driven gear was disassembled from the gearbox and a half of the gear tooth was removed by using the wire Electrical Discharge Machine (EDM). The procedure of running the system from 10-60 Hz and acquiring the signals for the same was repeated.
6. After the completion of this step, a full teeth was removed from the driven gear with EDM and same procedure of speed and data acquisition was repeated.

Figure 3.6: Top view of the straight bevel gearbox

3.3 Instrumentation and data analysis

Some important parameters that have to be controlled in order to obtain useful measurements for analysis are:

(i.) Sampling rate: The sampling rate is the frequency at which measurements are captured from the sensor or transducer.

(ii.) Sampling time: The sampling time is the length of time used for taking measurements.

(iii.) Number of samples: The number of samples refers to the quantity of individual measurements recorded.

The sampling rate, sampling time and number of samples are related as follows:

$$\text{Sampling rate x Sampling time} = \text{Number of samples}$$

The sampling rate selected should be 2.56 times greater than the highest frequency to be recorded, called Nyquist Frequency. Sampling at a rate higher than 2.56 times the maximum frequency of interest ensures that enough data is collected to reproduce the original signal. The vibration signal acquired continuously by an accelerometer in our experimental setup are in time-amplitude (acceleration) form. The sampling parameters are manually set in LabView software.

CHAPTER 4

SIGNAL PROCESSING TECHNIQUES

4.1 Signal Processing in Fault Diagnosis of Gearbox

Fault Diagnosis of gearbox is analyzing the system and to interpret the fault or failure present in the gearbox parts or system. As it has been discussed the fault in gearbox results in form of change of vibration signals obtained by a sensor mounted on the gearbox system. This sensor may be one of vibration sensors like velometer, vibration pickup, accelerometer or simple transducer. The output of this vibration sensor is in form of signal waves which carries information regarding condition of gearbox and type of faults present if any. Thus, study of such signals that carry so much of information is most important requirement in process of vibration analysis. Also the basic need is to choose appropriate signal processing technique which can effectively extract information from signals and can give a graphical representation

related to the fault present in the gearbox system.
As all the information of condition and faults are within the signal obtained it becomes very complex to analyze the signal. Few techniques were developed in past decades for processing of such signals. The most conventional technique is Time domain analysis. The signal obtained is always in time domain if no processing is carried out on the raw signal. But studies show that it was very difficult to detect faults of the gearbox using such conventional signal.
Also with change in working condition, type of signals obtained at transducer also changes. The signal obtained can be stationary or non-stationary in nature. Stationary signals are independent of time and have no effect of time on their amplitude, frequency or any other parameter. So frequency domain analysis can be effective method that can be used for system with stationary signals. While non-stationary signal property keeps on changing along with time. During normal working all systems exhibit stationary signals but during the start up or shut-down, the values and functions of signals change suddenly and result in non-stationary signals. As these signals vary with time, it is necessary to analyze the time based signal of the gearbox system. So a time- frequency domain analysis can be effective for analyzing non-stationary signals. Two basic and more pronounced techniques are Short-Time Fourier Transform (STFT) and Wavelet Transform.

Signals are functions that carry information about the behavior or attribute of some phenomenon. In real physical world, the quantities that exhibit variation in time or space can potentially be a signal that might help us to study status of physical system or other possibilities. The term signal is can be audio, video, speech, geophysical, radar, sonar, or musical is mentioned by IEEE Transaction on Signal Processing.
The field of information theory is to obtain information from signals. But signal also contain some noise within them. Usually term Noise is referred to undesirable information. It is necessary to separate the noise from signals to get accurate information. Various techniques are developed for this process to filter the information from the

signals obtained from physical system. These techniques are classified as signal processing techniques.

The vibration obtained from physical phenomenon is in form of signal. Conventionally these signals were analyzed by Fourier Transform (FT). Later the development in this introduced Fast Fourier Transform (FFT) which is used to obtain power spectrum of raw material. But FFT is only suitable for analyzing stationary signals and there is data loss observed. Recently Wavelet Transform has been proven effective for signal processing and is widely used in the field of fault diagnosis. This is effective for non-stationary data signals and is multi-resolution time-frequency method that highlights localized signal characteristics

4.2 Types of Techniques used in Signal Processing

From last many decades it has become necessary to develop techniques which are related to combination of various branches. One such combined branch of electronics and mechanical has been much in demand known as Electro-mechanical Engineering. In this, some physical systems are explained with help of various electronic circuits which can effectively carry same process and output. Also some methods which can be used to apply on mechanical systems to carry out an analysis process to understand the behavior of the system.
As we know that vibration of any system is obtained in form of signals with help of sensors like accelerometer, Vibrometer, and few others. It has become a most challenging task to keep the field of signal processing to be updated and to make it easy for various processes to be study with help of such methods. In past years some techniques used for analyzing the vibration signals of a system are discussed in this topic.
Firstly the most basic term that evolved was Time- domain. It was used for analyzing

the vibration signals for the very basic time. The signals which are produced by any system is in time domain as its all values are having relation with time of the process. In this method, we can observe that the signals had amplitude vs. time plot and amplitude showed the severity of any fault so we can conclude that the fault had reached its critical value or not. But it was not enough to know only about the severity of the fault.

Due to this, there was need of a new method to analyze the signal which can also predict the fault type and different parameters. Fourier Transform was invented which can transform time domain into frequency domain. The frequency domain helped the user to know the effects of different faults on the amplitude of system with respect to frequency and to relate that change with the fault present in the system. Still there was not so much accuracy of this technique to analyze the signals completely.

Later on came a new method into existence which was called as time- frequency domain. In this the plot was made for both frequency and time axis. This helped a lot for analyzing the system as it had time as well as frequency relation. With help of frequency domain we can get to know the type of fault and with help of time domain we can know the severity of the plot. So it was used for analyzing many systems and was effective for systems with linear motion and for same periodic time of vibrations. But during start-up or shut-down, it was observed that the system has non-linear motion and all above techniques discussed were of no use for the process of analyzing such system. So after a long time of research, a new technique was discovered which was for time-scale domain. This technique was known as Wavelet Transform. In this transform there are two main terms mother wavelet and scale factor. Mother wavelet is the basic function which is repeated by the system after irregular time period. And scale factor is the value by which the mother wavelet is scaled to adjust with original signal at a particular time.

4.3 Conventional Techniques for Signal Processing

Time domain analysis has been the most commonly used method for detecting the faults in any system. One can observe the severity of any fault after looking in the amplitude vs time plot whether the fault has reached its critical value or not. But it had its own limitations, like it did not provide sufficient information about the occurrence of the fault. So, Fourier Transform techniques were proposed which can transform time domain into frequency domain. The frequency domain helped the user to know the effects of different faults on the amplitude of system with respect to frequency and to relate that change with the fault present in the system. Later, time-frequency domain methods/techniques came into existence which overcame the shortcomings of the Fourier Transforms. The shortcoming of not detecting non-linearity from the signals led to the development of wavelet techniques which became very famous because of their simplicity and easy handling of the data. The assumptions made for Fourier spectral may give misleading results and some of them are described as follows:
(a) Fourier spectrum requires many additional components to define harmonic components globally applicable for simulation of non-stationary and non-uniform data.
(b) Secondly, it considers linear superposition of different trigonometric functions therefore, it requires a large number of harmonic components for analyzing the signals.

Conventional techniques cannot represent both non-stationary and non-linear signal systems and can mislead the results of energy distribution for frequency range, there is a need for a new technique that can be used more effectively for processing non stationary signals.

4.4 Empirical mode decomposition

In this section, Huang [18] presented a new data analysis method based on the empirical mode decomposition (EMD) method, which will generate a collection of intrinsic mode functions (IMF). The decomposition is based on the direct extraction of the energy associated with various intrinsic time scales, the most important parameters of the system. Expressed in IMFs, they have well-behaved Hilbert transforms, from which the instantaneous frequencies can be calculated. Thus, any event can be localized on the time as well as the frequency axis. The decomposition can also be viewed as an expansion of the data in terms of the IMFs. Then, these IMFs, based on and derived from the data, can serve as the basis of that expansion which can be linear or non-linear as dictated by the data that is complete and almost orthogonal. Most important of all, it is adaptive. As will be shown later in more detail, locality and adaptivity are the necessary conditions for the basis for expanding non-linear and non-stationary time series, orthogonality is not a necessary criterion for basis selection for a non-linear system. The principle of this basis construction is based on the physical time scales that characterize the oscillations of the phenomena. The local energy and the instantaneous frequency derived from the IMFs through the Hilbert transform can give a full energy-frequency-time distribution of the data. Such a representation is designated as the Hilbert spectrum, it would be ideal for non-linear and non-stationary data analysis.

A general method is introduced here which requires two steps in analysing the data as follows. The first step is to preprocess the data by the empirical mode decomposition method at which the data are decomposed into a number of intrinsic mode function components. Thus, data will be expanded in a basis derived from the data. The second step is to apply the Hilbert transform to the decomposed IMFs and construct the energy-frequency-time distribution, designated as the Hilbert spectrum, from which the time localities of events will be preserved. In other words, the need of the instantaneous frequency and energy rather than the global frequency and energy defined by the Fourier spectral analysis. Therefore, before going any further, the clarification of the definition of the instantaneous frequency is necessary.

For an arbitrary time series, $X(t)$, its Hilbert Transform can be obtained as, $Y(t)$, as

$$Y(t) = \frac{1}{\pi} PV \int_{-\infty}^{+\infty} \frac{x(t')}{t - t'} \, dt' \tag{4.1}$$

where P indicates the Cauchy principal value. This transform exists for all functions of class L^p. With this definition, $X(t)$ and $Y(t)$ form the complex conjugate pair, so as to have an analytic signal, $Z(t)$, as

$$Z(t) = X(t) + \iota Y(t) = a(t) e^{\iota \theta(t)} \tag{4.2}$$

where,

$$a(t) = \sqrt{x^2 + y^2},$$

and

$$\theta(t) = \arctan\left(\frac{y}{x}\right) \tag{4.3}$$

$$\omega = \frac{d\theta(t)}{dt} \tag{4.4}$$

This local restriction suggests a method to decompose the data into components for which the instantaneous frequency can be defined. The examples presented above, however, actually lead to the definition of a class of functions, based on its local properties, designated as intrinsic mode function for which the instantaneous frequency can be defined everywhere. The limitation of interest here is not on the existence of the Hilbert transform which is general and global, but on the existence of a meaningful instantaneous frequency which is restrictive and local.

An intrinsic mode function (IMF) is a function that satisfies two conditions:

(a) In the whole data set, the number of extrema and the number of zero crossings must either equal or differ at most by one.

(b) at any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero.

Having defined IMF, it will be shown that the definition given in equation 4.4 gives the best instantaneous frequency. An IMF after the Hilbert transform can be expressed as in equation 4.2. If a Fourier transform on $Z(t)$ is performed, then

$$\begin{aligned} F(\omega) &= \int_{-\infty}^{+\infty} a(t)e^{\iota\theta(t)}e^{-\iota\omega t}\,dt \\ &= \int_{-\infty}^{+\infty} a(t)e^{\iota\theta t-\omega t}\,dt \end{aligned} \tag{4.5}$$

giving result as,

$$\frac{d}{dt}(\theta(t) - \omega t) = 0 \tag{4.6}$$

therefore, equation 4.4 follows. Although mathematically, the application of the stationary phase method requires a large parameter for the exponential function, the adoption here can be justified if the frequency is high compared with the inversed local time scale of the amplitude variation. Therefore, this definition represents best for gradually changing amplitude. Even with this condition, this is still a much better definition for instantaneous frequency than the zero-crossing frequency.

As given in equation 4.6 and the simple analogy given in equations 4.2 - 4.4, the frequency defined through the stationary phase approximation agrees also with the best fit sinusoidal function locally therefore, the need of a whole oscillatory period is not needed to define a frequency value. It can be defined for every point with the value changing from point to point. In this sense, even a monotonic function can be treated as part of an oscillatory function and have instantaneous frequency assigned according to equation 4.4. Any frequency variation is designated as frequency modulation. There are actually two types of frequency modulations, the inter-wave and the intra-wave modulations. The first type is familiar as the frequency of the oscillation is gradually changing with the waves in a dispersive system. Technically, in the dispersive waves, the frequency is also changing within one wave, but that was not emphasized either for convenience or for lack of a more precise frequency definition. The second type is less familiar but it is also a common phenomenon if the frequency changes from time to time within a wave its profile can no longer be a simple sine or cosine function. Therefore, any wave-profile deformation from the simple sinusoidal form implies the intra-wave frequency modulation. In the past such phenomena were treated as harmonic distortions. In order to use this unique definition of instantaneous frequency, the arbitrary data set needed to be reduced into IMF components from which an instantaneous frequency value can be assigned to each IMF component. Consequently, for complicated data, it can have more than one instantaneous frequency at a time locally. The empirical mode decomposition method is discussed to reduce the data into the needed IMFs.

CHAPTER 5

RESULTS & DISCUSSIONS

5.1 Introduction

The vibration signals emanating from a running gearbox are non-stationary. If a fault (tooth deflection or a mismatch of gears) adds up to this non-stationary signal, the overall signal becomes non-linear. Higher impulses for gear related faults are identified in the gearbox signals for localized faults. These faults can be seen around the gear mesh frequency appearing as side bands as deduced from the literature. In this chapter, signals for the healthy gears have been acquired and analyzed. The fault seeded in the pinion is the one missing tooth i.e. a tooth has been removed using electrical discharge machining (EDM). The data for the healthy and faulty gears have been taken for 30, 35, 40 and 45 Hz. EMD technique has been applied to both healthy and faulty signals. After this, IMFs have been generated and analysed.

5.2 Discussion of results

The experiments for healthy and faulty gears at different running speeds are implemented in the following phased manner:

1. The signals are taken using data acquisition with the help of an accelerometer.
2. LabView software has been used as an interface to record the signals in the form of time waveform (time-acceleration) signals. These signals are then imported to the MATLAB software.

5.2.1 Analysis of time waveform and frequency domain for healthy and faulty gears

Time waveform and frequency domain of the healthy gear (HGB) and one missing tooth gear (OMTGB) at 30 Hz have been shown in Figures 5.1(a), 5.1(b), 5.1(c) and 5.1(d) respectively. Time waveform plot has been shown for one second, whereas the frequency domain plots have been shown for two ranges - one is from 0-100 Hz and second range is around the gear mesh frequency.

The first question comes into the mind of an experimentalist is whether the amplitude of a gear goes up or down with the introduction of a fault in the system in comparison to the healthy gear. In this regard, the rms values of the signals taken at various speeds for healthy and faulty gears are shown in Table 5.1. RMS values for one missing tooth gearbox at all speeds is higher than the values of healthy gear box. These values are also indicative of a faulty system, but not sure what type of fault is present in the system.

Table 5.1: RMS value of all signals at various speeds

HGB30	HGB35	HGB40	HGB45
0.023	0.026	0.031	0.046
OMTGB30	OMTGB35	OMTGB40	OMTGB45
0.042	0.045	0.058	0.064

A gearbox will always have a strong vibration component at the GMF regarded as the first harmonic ($1X f_{mesh}$), and it is one of the fault frequencies used in machinery monitoring. It is inferred from the frequency domain plots for healthy and faulty gears that for OMTGB a number of frequency spikes get enhanced in comparison to healthy gear as shown in Figure 5.1(c) and Figure 5.1(d). The formula for calculating the gear mesh frequency (GMF) is:

$$\text{GMF} = \text{No. of teeth on pinion x running speed (Hz)}$$

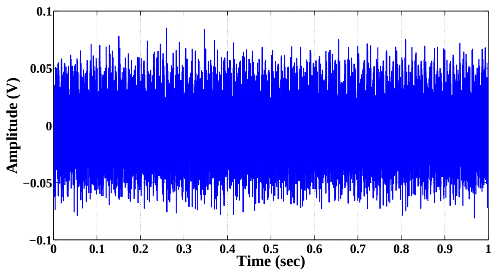
Figure 5.1(e) and Figure 5.1(d) show the plot of GMF spectrum at 30 Hz for a healthy and a faulty gear. The GMF for gear at this speed is 540 Hz (refer 5.2. In these plots, there are no significant peaks seen around 540 Hz, but for OMTGB, a number of side bands have emerged suggesting a fault in the system. Even the amplitude of GMF peak at 540 Hz is seen to be increased in OMTGB.

Similar results have been noticed for healthy gear and fault gear at speeds 35 Hz, 40 Hz and 45 Hz in Figures 5.2, 5.3 and 5.4. With the increase of speed, a rise in the amplitudes of running frequency and gear mesh frequencies has been noticed for the remaining pre-determined speeds.

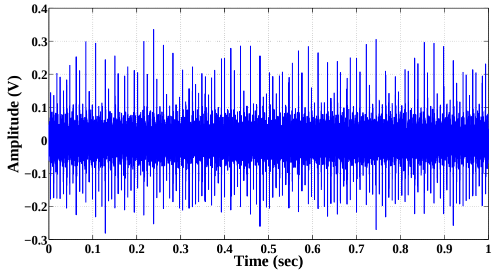
Table 5.2: Gear Mesh frequency of straight bevel gearbox at different speeds

		GMF
HGB30	OMTGB30	540
HGB35	OMTGB35	630
HGB40	OMTGB40	720
HGB45	OMTGB45	810

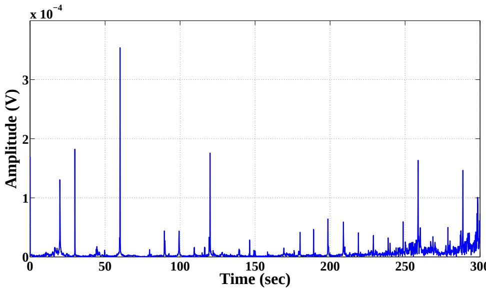
The pattern and frequency of sidebands around gear mesh frequency in the spectrum of faulty gearbox gives us an idea about the varying conditions of a faulty gearbox from healthy one is due to the distortion occurring in a toothed gear. There exist a minimal amount of knowledge as this feature becomes a problem when analysing non-stationary signals. Thus, it become difficult to analyse at this point the nature of the defect.



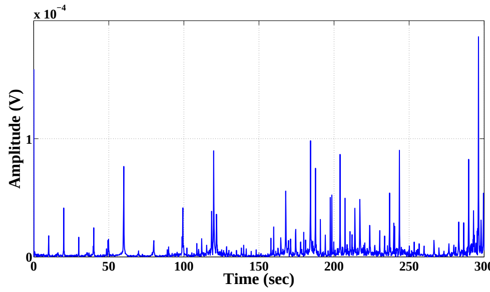
(a) Time waveform of HGB at 30 Hz



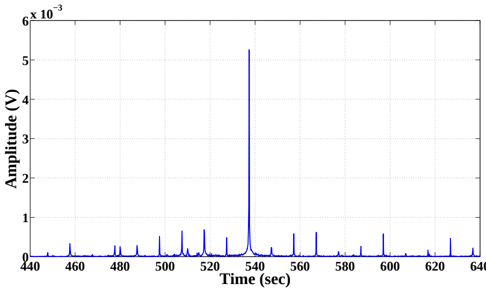
(b) Time waveform signals of OMT at 30 Hz



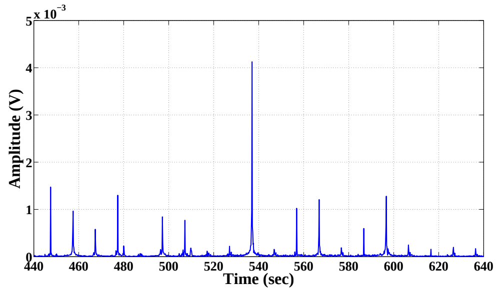
(c) Frequency spectrum of HGB at 30 Hz



(d) Frequency spectrum of OMT at 30 Hz



(e) Gear Mesh Frequency spectrum at 30 Hz



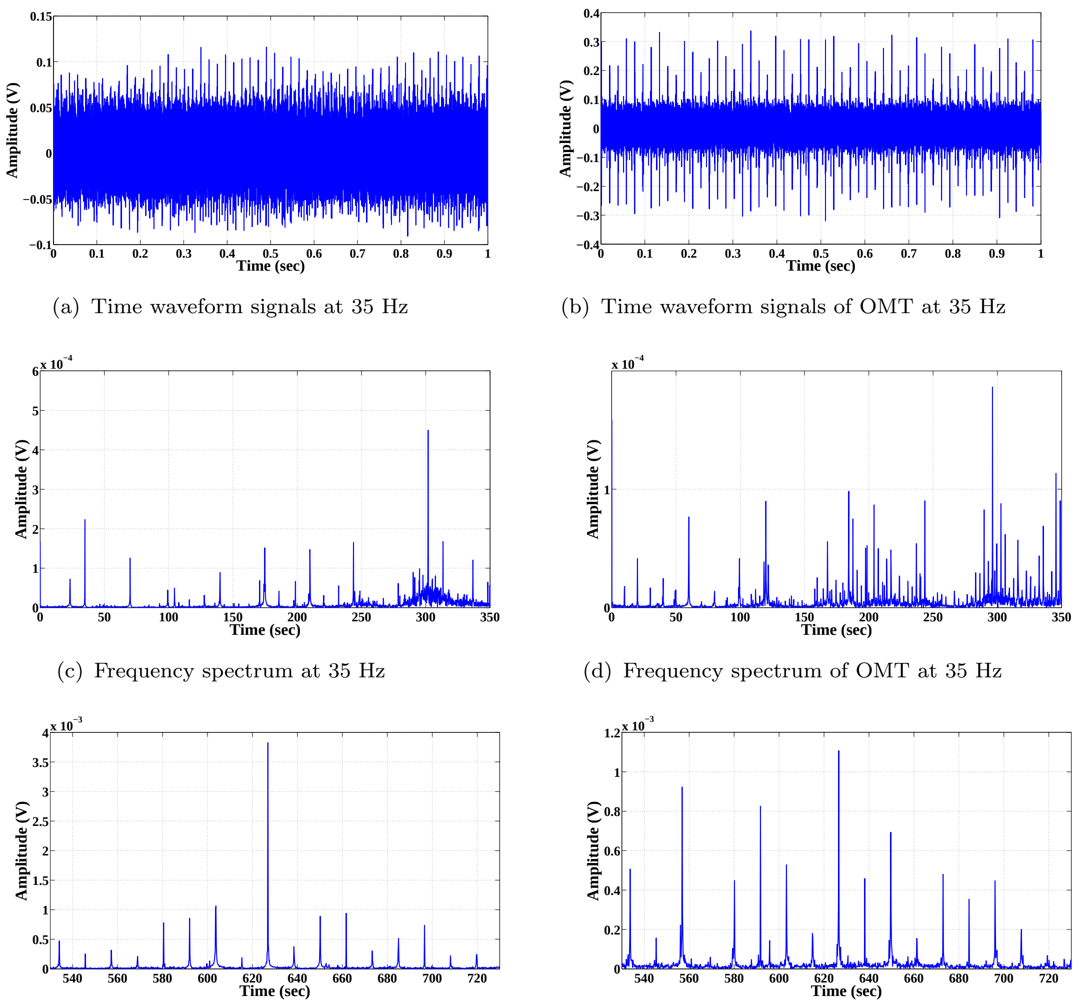
(f) Gear Mesh Frequency spectrum of OMT at 30 Hz

Figure 5.1: Time waveform, frequency domain of Healthy and Faulty gear at 30 Hz

5.2.2 EMD technique applied to healthy and faulty gears

EMD algorithm is applied to healthy and faulty gear data for generating Intrinsic mode function (IMF) at pre-decided speeds. First eight IMFs have been generated for every signal irrespective of whether it is healthy or faulty to extract the fault information as shown in Figures 5.5, 5.7, 5.9 and 5.11 for healthy gears and in Figures 5.6, 5.8, 5.12 and 5.12 for faulty gears. The IMF's carry the important information regarding the faults. The obvious amplitude-demodulated features can be seen from IMF's of higher energy modes.

The comparison of IMFs of a healthy gear and a faulty gear at 30 Hz shows that



(a) Time waveform signals at 35 Hz

(b) Time waveform signals of OMT at 35 Hz

(c) Frequency spectrum at 35 Hz

(d) Frequency spectrum of OMT at 35 Hz

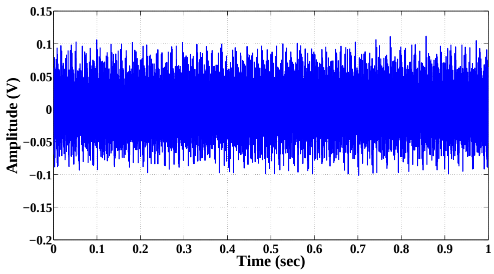
(e) Gear Mesh Frequency spectrum at 35 Hz

(f) Gear Mesh Frequency spectrum of OMT at 35 Hz

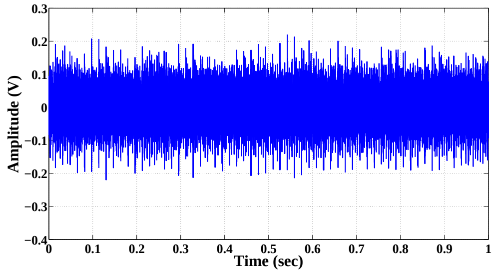
Figure 5.2: Time waveform, frequency domain of Healthy and Faulty gear at 35 Hz

for a faulty gear the overall amplitude of faulty gear increases with the introduction of a fault refer, Figures 5.5 and 5.6. A closer look in the C2 IMF of faulty gear at 30 Hz clearly shows up the presence of higher frequencies and the spacing between the two consecutive time waveforms is equal to the fault frequency of the gear i.e. the gear mesh frequency. Similar results are reported for the faulty gears at other pre-determined speeds.

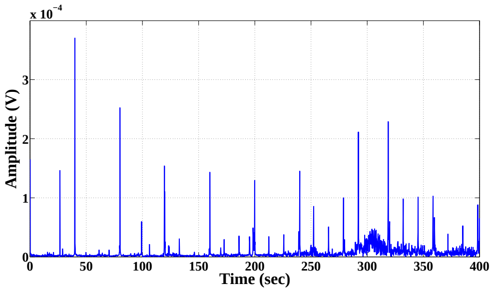
Table 5.3 shows various energies associated with IMF's of healthy and faulty gear signals. Even this comparison shows that with the faulty gear and increase of speed the corresponding and significant changes in various energies associated are noticed.



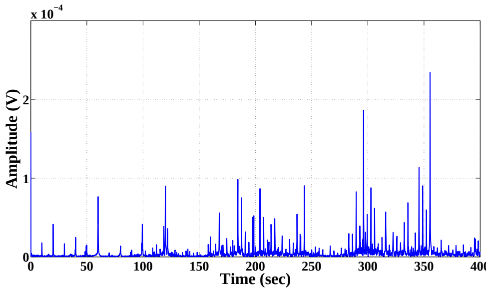
(a) Time waveform signals at 40 Hz



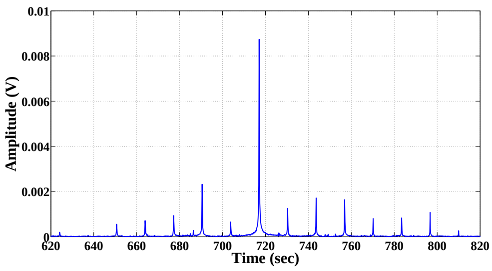
(b) Time waveform signals of OMT at 40 Hz



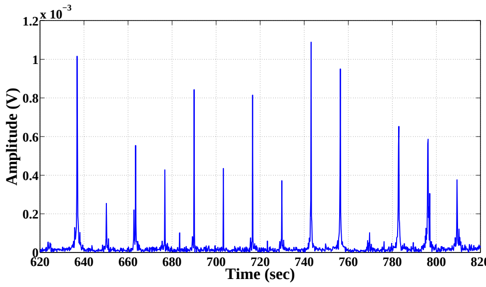
(c) Frequency spectrum at 40 Hz



(d) Frequency spectrum of OMT at 40 Hz



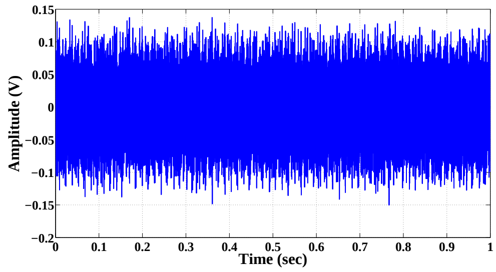
(e) Gear Mesh Frequency spectrum at 40 Hz



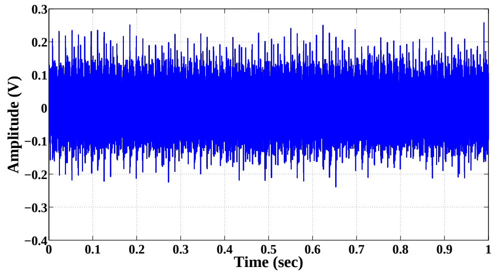
(f) Gear Mesh Frequency spectrum of OMT at 40 Hz

Figure 5.3: Time waveform, frequency domain of Healthy and Faulty gear at 40 Hz

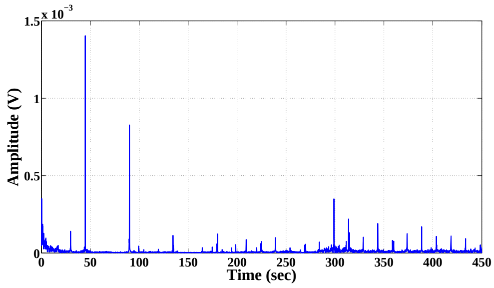
In this chapter, time wave forms, the rms values for all the signals, frequency domains and IMF's for the healthy and faulty gears have been shown for the diagnosis of faulty gears.



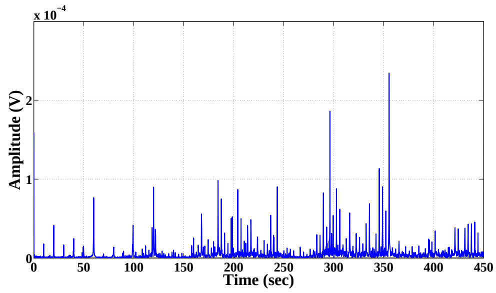
(a) Time waveform signals at 45 Hz



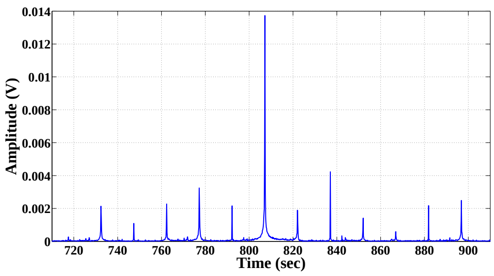
(b) Time waveform signals of OMT at 45 Hz



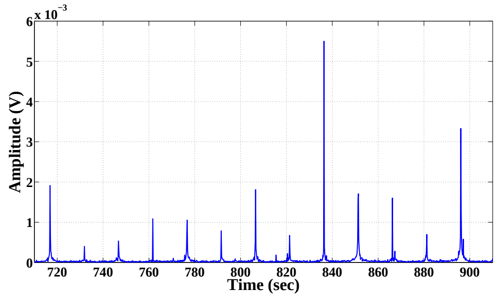
(c) Frequency spectrum at 45 Hz



(d) Frequency spectrum of OMT at 45 Hz



(e) Gear Mesh Frequency spectrum at 45 Hz



(f) Gear Mesh Frequency spectrum of OMT at 45 Hz

Figure 5.4: Time waveform, frequency domain of Healthy and Faulty gear at 45 Hz

Table 5.3: Various energies associated with IMF's of healthy and faulty gear signals

HGB	P, Total Power	Pav, Average power	Et, Total Energy	OMTGB	P, Total Power	Pav, Average power	Et, Total Energy
HGB30	3.82	0.0001	0.0007	OMTGB30	7.365	0.00025	0.00149
HGB35	5.594	0.0002	0.0010	OMTGB35	12.171	0.000371	0.0027
HGB40	5.43	0.00016	0.0010	OMTGB40	19.59	0.00059	0.00382
HGB45	17.12	0.0005	0.0033	OMTGB45	21.073	0.00064	0.0041

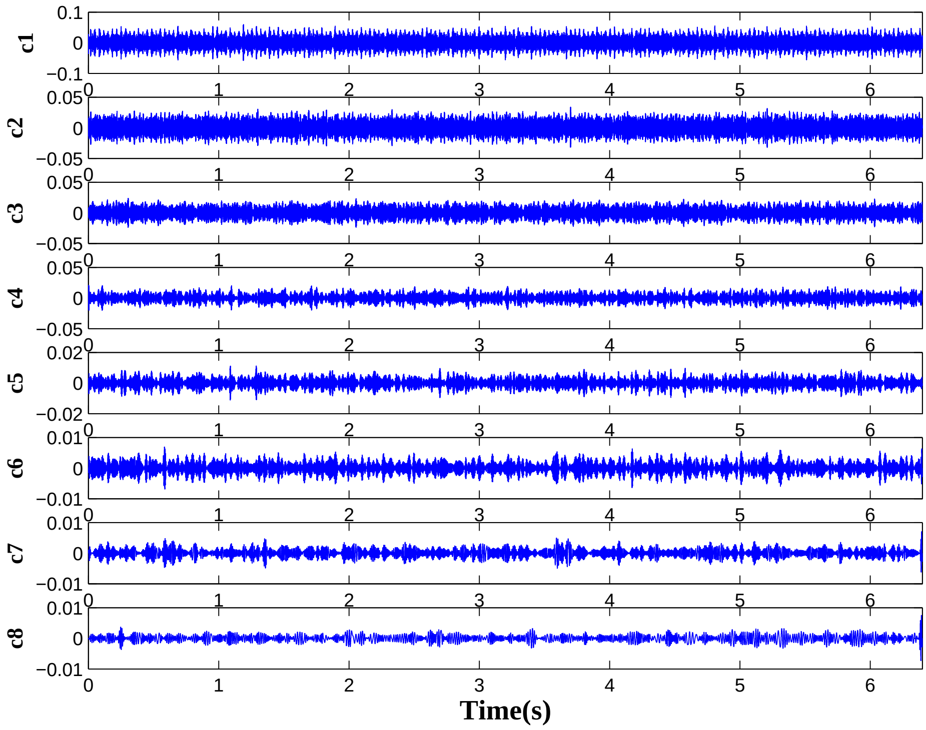


Figure 5.5: IMF of HGB at 30 Hz

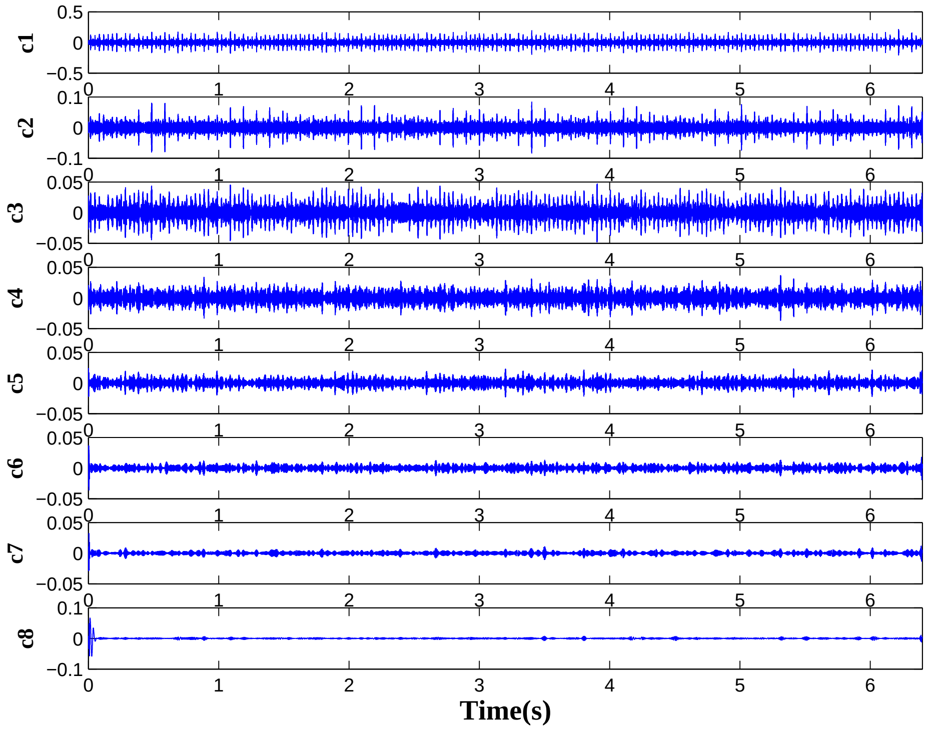


Figure 5.6: IMF of OMTGB at 30 Hz

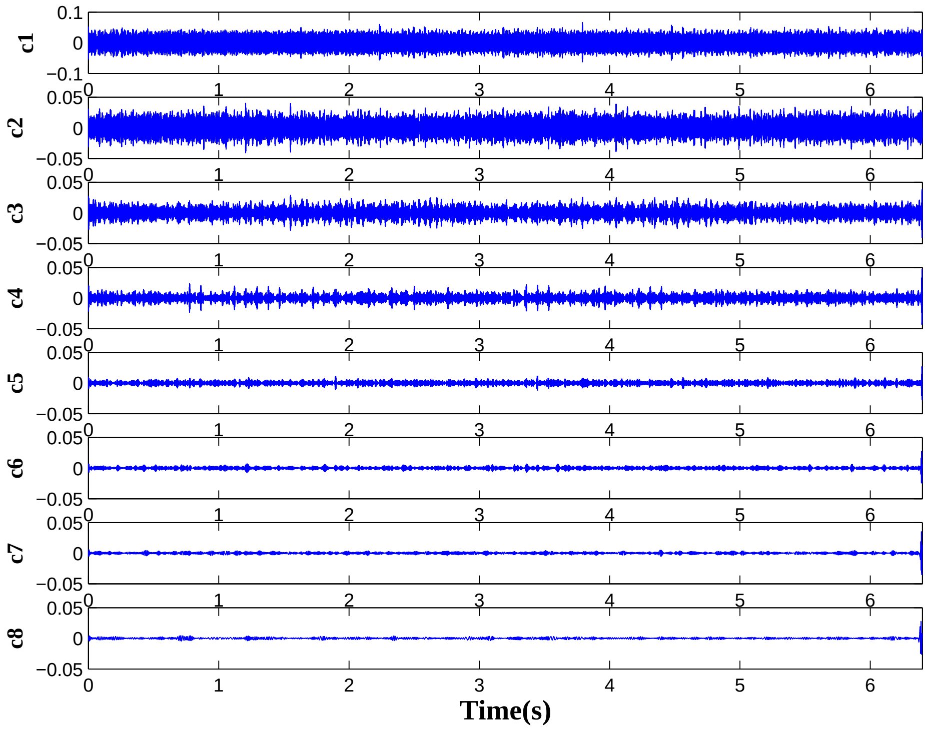


Figure 5.7: IMF of HGB at 35 Hz

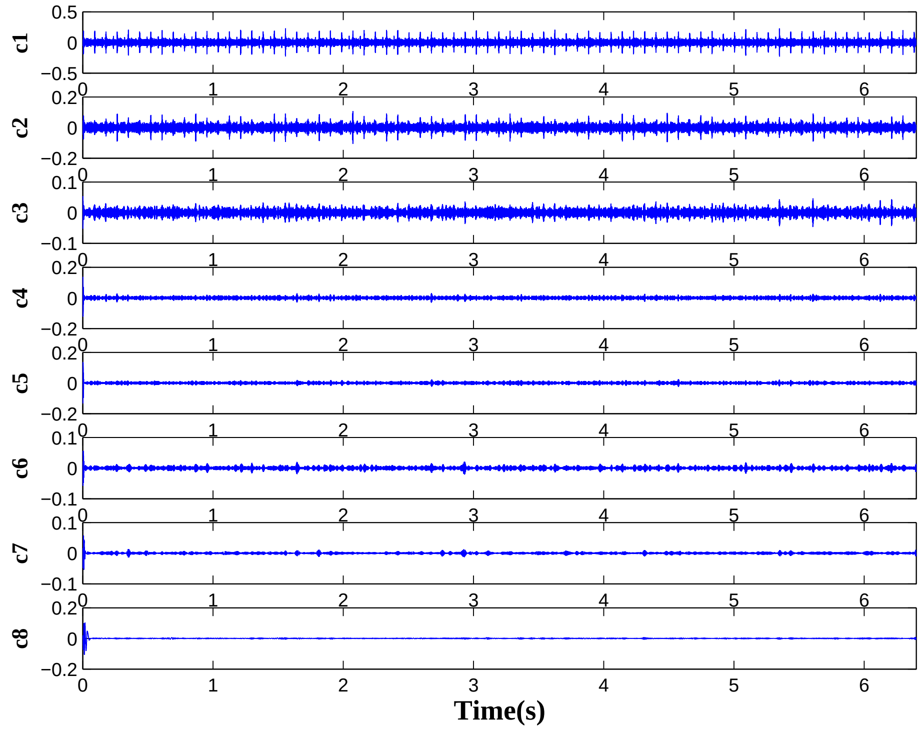


Figure 5.8: IMF of OMTGB at 35 Hz

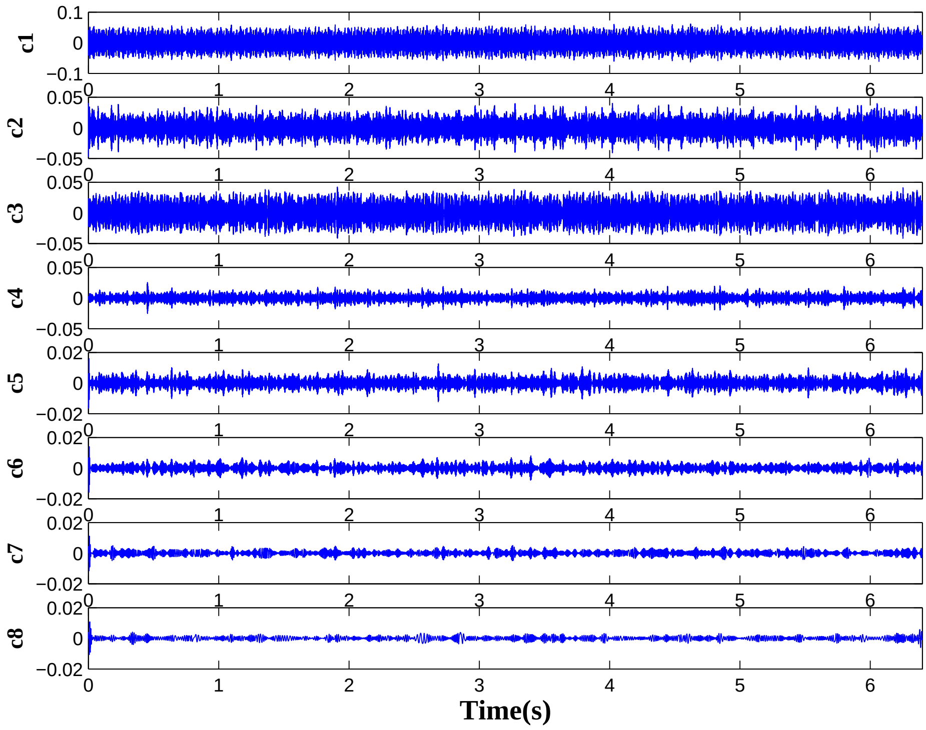


Figure 5.9: IMF of HGB at 40 Hz

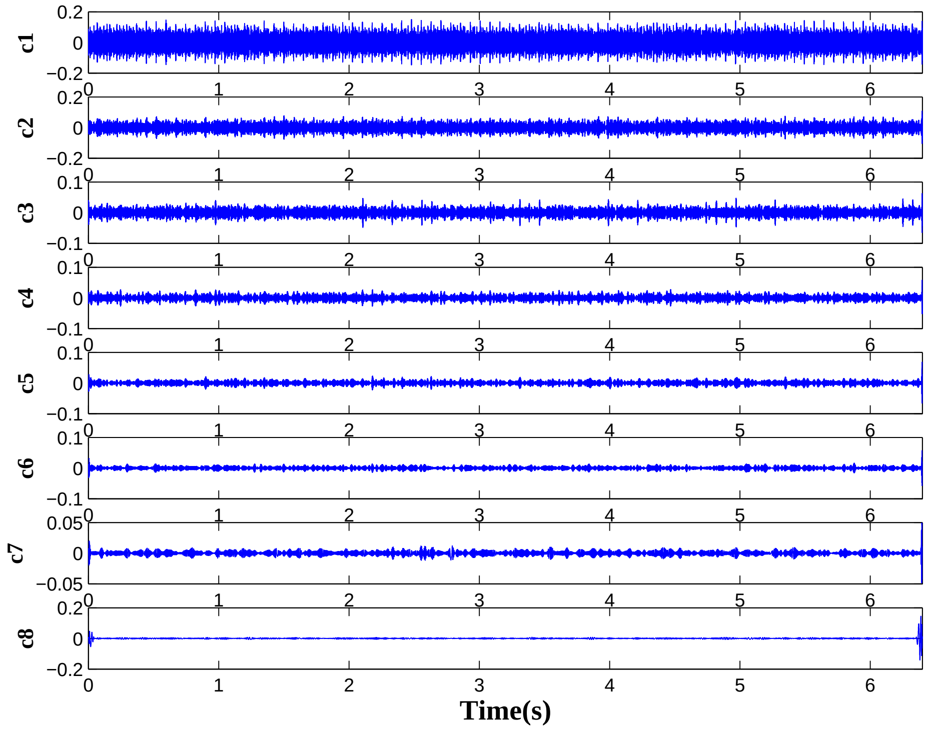


Figure 5.10: IMF of OMTGB at 40 Hz

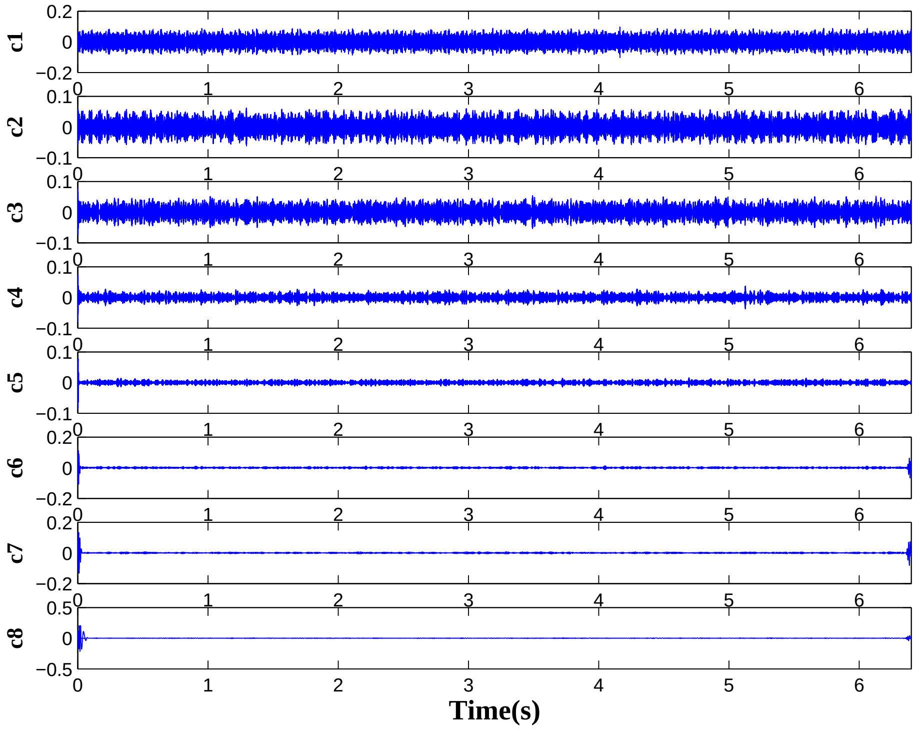


Figure 5.11: IMF of HGB at 45 Hz

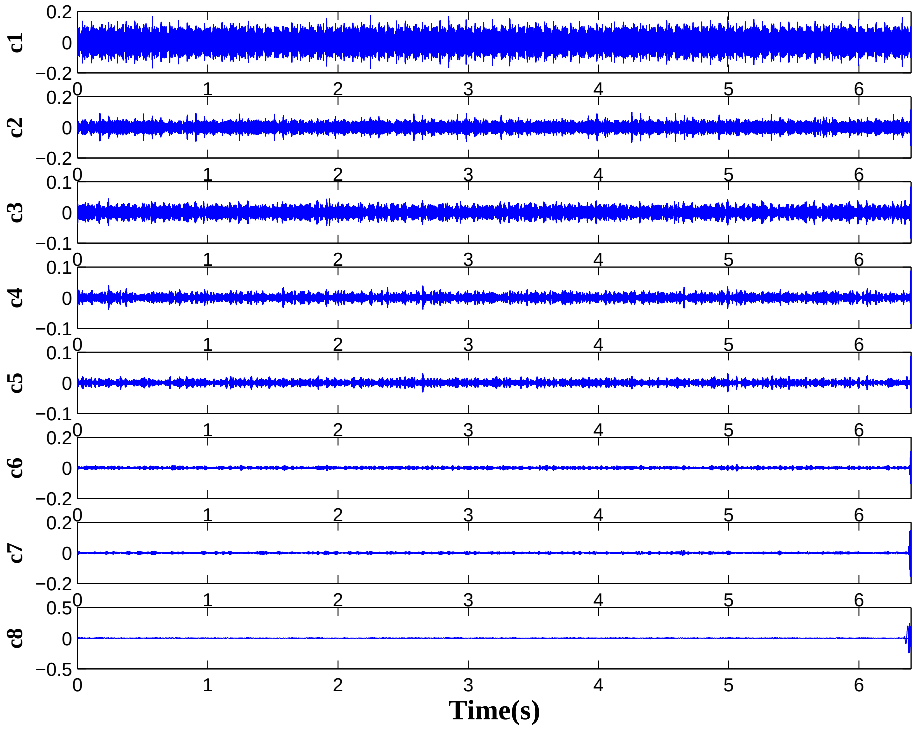


Figure 5.12: IMF of OMTGB at 45 Hz

CHAPTER 6

CONCLUSIONS & FUTURE SCOPE

6.1 Conclusions and Future Scope

The present study is based on the detection of a faulty gear in comparison to a healthy gear. The time and frequency responses of the vibration signatures for healthy and faulty gears have been analyzed. Applications and developments of algorithms for the detection of the gear tooth damage from the vibration signatures has been done. The experimental test rig for detecting the damages of gear in rotor system were established using a straight bevel gearbox. The comparison between healthy and faulty gears has been shown to demonstrate the effect of increased amplitude of vibration levels in faulty gears. The experimental results were examined in the time domain, the frequency domain and the joint time-frequency domain Empirical Mode Decomposition (EMD). Based on results of the present study, conclusions have been drawn as follows:

i. The data acquired in the form of time waveform does not provide a clear cut difference between healthy and faulty gear. As the acquired signals contain very useful information about the condition of the gear but the much vital information is not revealed because of the complex nature of the signals.

ii. The rms values of the healthy and faulty gears also help to investigate about the presence of a fault in the system but cannot pinpoint what type of fault sis present in the system . Further more, frequency domain analysis can provide more clear information about the failure with the increase in the amplitude of side band components. Observing the frequency spectrum signals of a healthy gearbox system clearly gave a peak at gear mesh frequency and it increased with an increase of speed for the same type of fault. Significant increase in the amplitude of side bands has also been noticed in frequency domain of the faulty gears. Thus, this technique plays an important role to know the changed conditions in a system. But still cannot ascertain what type of faults is prevalent in the system.

iii. Empirical Mode Decomposition (EMD) is adapted to analyse the time domain signal to provide an accurate identification of the damage in the gear tooth. This technique gives a clear distinction between healthy and faulty gear, but it also provides an effective way to identify the type or location of the gera fault. Based on the local characteristic time scale of the signal this technique can decompose the complicated signal into a number of intrinsic mode functions. Frequency components contained in each IMF not only relates to the sampling frequency, but also changes with the signal itself. Therefore, EMD could be suitable for non-linear and non stationary signal processing and applied to extract gear fault feature effectively.

6.2 Recommendations for future work

Similar type of experimentation can be carried out for revealing certain other type and location of faults such as broken tooth, cracked tooth, or the faults existing in more than one tooth on same gear using various types of sensors to validate the results coming from vibration sensors. EMD technique can be researched further for identifying various kinds of faults in other areas of condition monitoring like bearings and combination of faults like: bearings and gear faults etc.

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