B. TECH. PROJECT REPORT

On

Condition Monitoring & Fault Diagnosis of Bevel Gears

BY

Anubhav Agrawal (140003007)

Harsh Mehta (140003016)

DISCIPLINE OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

December 2017

Condition Monitoring & Fault Diagnosis of Bevel Gears

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degrees

of

BACHELOR OF TECHNOLOGY

in

MECHANICAL ENGINEERING

Submitted by:

Anubhav Agrawal (140003007)

Harsh Mehta (140003016)

Guided by:

Dr. Anand Parey

Mechanical Engineering

Associate Professor, IIT INDORE

INDIAN INSTITUTE OF TECHNOLOGY INDORE

December 2017

CANDIDATE’S DECLARATION

We hereby declare that the project entitled “Condition Monitoring & Fault Diagnosis of Gears” submitted in partial fulfillment for the award of the degree of Bachelor of Technology in Mechanical Engineering completed under the supervision of **Dr. Anand Parey, Mechanical Engineering, Associate Professor,** IIT Indore is an authentic work.

Further, we declare that we have not submitted this work for the award of any other degree elsewhere.

Anubhav Agrawal (140003007)

Harsh Mehta (140003016)

CERTIFICATE by BTP Guide

It is certified that the above statement made by the students is correct to the best of my knowledge.

Dr. Anand Parey

Associate Professor, Mechanical Engineering, IIT Indore

PREFACE

This thesis on “Condition Monitoring & Fault Diagnosis of Gears” is prepared under the supervision of Dr. Anand Parey.

In this project we have performed Vibration Monitoring on bevel gears. We have used Machinery Fault Simulator (MFS) to carry out our analysis. Three different bevel gear systems were used-

- Healthy gearbox;
- Chipped teeth pinion;
- Broken teeth pinion.

A tri-axial accelerometer has been used to collect vibration signals from the gear box at different frequencies along different axes. Finally, we have analyzed the vibration signals through the Waveform and Spectral Techniques via MATLAB software. We were also able to analyze the signals at different positions of sensor on the gearbox.

Anubhav Agrawal

Harsh Mehta

B. Tech. IV Year

Discipline of Mechanical Engineering

IIT Indore

ACKOWLEDGEMENT

We would like to express our sincere gratitude to our project guide Dr. Anand Parey for his never ending encouragement and innovative ideas in commencing our project on “Condition Monitoring & Fault Diagnosis of Gears”. Whenever we had any problem during this project he was always behind us to help us.

We would also like to thank Mr. Dada Saheb Ramteke, the Phd. Scholar who helped us in running our experiment smoothly. We can’t end our acknowledgement without thanking the lab assistant, Mr. Sandeep Patil for his assistance and cooperation.

Anubhav Agrawal

Harsh Mehta

B. Tech. IV Year

Discipline of Mechanical Engineering

IIT Indore

ABSTRACT

Gears are used to provide speed and torque conversion from a rotating power supply to different parts of body. It is widely used in industrial, civilian and military applications, for example in helicopters, wind turbines, milling machines, etc. Gears are constantly in use under various operating conditions. Under such harsh conditions there is always a chance that faults may develop on gears and if they go undetected, they may turn catastrophic. In this project we have talked about the different condition monitoring techniques that can predict the defects in gears and can give heads up to the operator.

Gears undergo huge stresses and fatigue sets in ultimately leading to failure, if not prevented. Condition Monitoring refers to the assessment of the condition of a machine via a parameter which changes with a slight change in the operation of the machine, mainly due to faults in its parts or changes in working environment. Condition Monitoring coupled with fault diagnosis is a form of preventive maintenance. Vibration Monitoring is the art of using vibration information (waveform, spectral. phase, etc.) to aid in detecting faults in a system.

Not much work has been done on the condition monitoring of bevel gears for various practical and applicable conditions. In this thesis, we primarily focused our work on Vibration Monitoring. Vibration Monitoring, as the name suggests, is a technique which monitors the condition of any machine by analyzing the vibrations taken from the different critical locations of machine. This is a simple technique with high sensitivity towards defects. With some basic knowledge and softwares, this technique can be used for condition monitoring of machines.

This technique further consists of two different approaches- Waveform and Spectral Analysis. In waveform analysis we monitor the machine by plotting graphs between vibration's magnitude and time. In spectrum analysis plot between magnitude of vibrations and frequency is used. The time domain signals can be converted to frequency domain signals with the help of Fast Fourier Transform (FFT).

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INTRODUCTION

1.1 CLASSIFICATION OF GEARS

Gear systems are classified on the basis of *orientation of the rotational axes of the gears* as:

Parallel-shaft gears: The shaft axes are in the same plane and parallel to one another. Spur gears have straight teeth, whereas helical gears have inclined teeth.

Figure 6.1: Spur and Helical Gears

Intersecting-shaft gears: The shaft axes intersect and the gears are not in same plane.

Non-parallel, non-intersecting shaft gears: These are non-coplanar with an alignment between 0 and 90º. This category includes hypoid gears, worm gears etc.

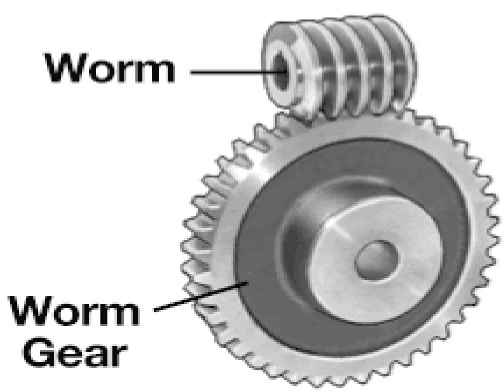

Figure 1.7: Worm Gear

1.2 BEVEL GEARS

There are basically two types of bevel gears: ***straight*** and ***spiral bevel gears***. The tapered nature of the bevel gear results in an axial thrust on the support bearings[1].

Straight bevel gears: These gears have straight teeth cut along the pitch cone that if extended would intersect with the shaft axis [1]. They are used in automobile gear systems, industrial applications and low-speed drives where vibrations and noise may not be significant.

Spiral bevel gears: These ensure smoother and quieter operation as compared to straight-tooth gears as the curved and oblique teeth ensure gradual engagement with higher contact ratio. The most commonly used spiral angle for these gears is 35°. Spiral bevel gears are usually employed for high-speed applications (typically above 300 m/min and large speed reduction ratio applications [1].

Figure 1.8: Straight and Spiral Bevel Gears

Zero bevel gears have curved teeth with zero spiral angles. Strength wise, they fall in between straight bevel and spiral gears and are therefore generally employed for medium-load applications [1]. The two tooth ends are in the same plane as the gear axis and the pressure angle ranges from 14.5° to 25°.

Figure 1.9: Zero Bevel Gear

Miter bevel gears have the same number of teeth with their shafts intersecting at 90° (45° pitch angle for the two gears). They may have straight or spiral tooth profile.

1.3 GEAR MATERIALS & MANUFACTURING

- ***Ferrous metals and alloys*** include cast iron, plain carbon and alloy steels, stainless steel, sintered steels.
- ***Non-ferrous alloys*** include copper, aluminium, zinc and magnesium alloys.
- ***Non-metals*** include plastics and ceramics.

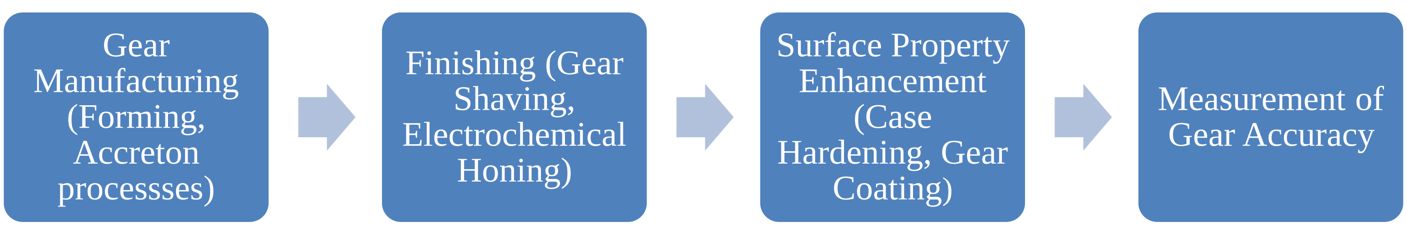

Figure 1.10: Steps involved in Gear Manufacturing

2

TYPES OF GEAR FAULTS

There are many modes of gear failure. One mode of failure may initiate another mode of failure. The modes of gear failure include:

PITTING/ SPALLING

Pitting is a fatigue effect which occurs due to higher Hertzian contact stresses than the surface can stand [2]. The maximum shear stress occurs below the surface, starting a crack which breaks out and leaves a small, smooth bottomed crater [2].

There are two types of pitting: ***initial*** and ***progressive pitting***.

Initial pitting usually occurs near, but not on the pitch line, in the region where the oil film is thin but there is still a sliding velocity [2]. Progressive pitting occurs when the load redistribution associated with initial pitting is not sufficient to reduce stresses below the fatigue limit [2].

Spalling is a form of pitting which leads to breakaway of hardened case. It occurs due to a transition from a hard outer case to relatively soft inner material. It also occurs due to metallurgical defects .

Figure 2.1: Pitting on a tooth surface

SCUFFING

Scuffing occurs when the oil film breaks down to allow metal to metal contact [2]. This leads to local welding, followed by shearing and subsequent tearing of the surface. There are two mechanisms which lead to oil film breakdown:

The ***cold scuffing*** is not common and can be avoided by reducing tooth surface roughness, increasing oil viscosity or using extreme pressure oils [2].

The normal type of ***"warm-scuffing"*** generates oil film breakdown by raising the temperature of the oil film locally to the point where the oil film can no longer maintain the gear tooth surface apart [2].

The scuffing pattern ultimately extends throughout the flank, constantly tearing the surface. Re-establishing the oil-film on the highly rough surface is not possible.

Figure 2.2: Scuffing on a surface

TOOTH-WEAR

Wear involves steady removal of metal from the gear flank usually over the whole face and may either give the appearance of lapped surface or may give a surface which is grooved in the sliding direction and so looks similar to scuffed surface at first site [2]. There are two distinct modes of wear- ***abrasive and adhesive.***

- **Abrasive wear** occurs due to mechanical contact with hard abrasive particles. Removal of abrasive from the oil can prevent this type of wear.

- **Adhesive wear** occurs when the pressure due to mechanical contact is sufficient to cause local plastic deformation and adhesion.

Figure 2.3: Tooth wear

ROOT CRACKING

This failure starts from small stress raisers in the root of the tooth [2]. It is tooth bending fatigue failure i.e. cracking under repeated stresses much lower than the ultimate tensile stress [2]. The likelihood of it is greatly enhanced by the presence of surface imperfections.

Figure 2.4: Fatigue crack in gear tooth root fillet

TOOTH TIP CHIPPING

Gear tooth tip chipping refers to a small piece of material breaking away from the tip of a tooth [2]. Local high stress concentration is the primary reason for such tooth failures. Other reasons include foreign material producing short-cycle failure and propagation of cracks and flaws from repeated cyclic loadings.

Figure 2.5: Chipped tooth

3

FAULT DIAGNOSIS TECHNIQUES & APPROACHES

FAULT DIAGNOSIS TECHNIQUES

Four techniques are commonly used in the monitoring of machinery conditions. They are:

- Infrared Thermography;
- Vibration Monitoring;
- Noise, sound and ultrasound techniques;
- Visual inspection;
- Lubrication condition and wear particle analysis.

GEAR FAULT DIAGNOSIS APPROACHES

The two types of approaches are: ***data-driven based methods*** and ***physical model-based methods***. Data-driven based methods rely on historical data collected from gearboxes to diagnose and predict their health conditions. Vibration signals, motor voltage, current signals, etc. can be used. Physical model based methods require a virtual system to mimic an existing object based on human understanding of it. The physical models of gearboxes can be divided into two categories: modulation-based models and dynamics-based models. Modulation based models are developed via the understanding of amplitude modulation, frequency modulation and phase modulation characteristics of vibration signals [2]. Dynamics based models are developed based on a fundamental analysis of gear mesh mechanism and dynamics, then, dynamic characteristics in various health conditions can be simulated, and fault symptoms can be revealed for fault detection and diagnosis [2].

The project is based on data-driven methods of vibration monitoring.

4

VIBRATION MONITORING

Vibration refers to the to and fro motion of a body from its equilibrium position or position of rest. Every rotating machine exhibits its own unique vibration characteristics.

Conceptual View of Monitoring and Analysis

Vibration monitoring is the strategic, timely, and routine collection of vibration data on specific machines [2]. The collected data highlights the trend for frequency and amplitude characteristics related to each machine. Assuming that the data is first collected when the machine is performing well, a "baseline" or norm can be established that is indicative of "good health" [2]. Any amplitude changes can easily be recognized if machine deterioration occurs.

Vibration analysis is the art of using vibration information (waveform, spectral. phase, etc.) to aid in the diagnosis of a machinery problem.

Pros to Vibration Monitoring

- Preventive Maintenance;
- Simple to use once set up;
- High sensitivity.

Cons to Vibration Monitoring

- Large involvement of instruments and softwares;
- Inadequate training and time-consuming;
- Data-driven based method, so vulnerable to incorrectness.

5
ANALYSIS TOOLS

Time Domain

- The time domain plots the amplitude versus time of the basic signal coming from the transducer.
- It reveals the true shape of the input signal (***waveform analysis***).
- The time waveform displays periodic/non-periodic, short/long term events- it is all there. Since signal-processing has not been applied, the information is virgin in content [2].

Frequency Domain

- Jean Baptiste Fourier determined that a periodic waveform could be broken down into a unique pattern of component sine waves (harmonic motion) that will combine to create the original [2].
- The conversion of time domain waveform to the frequency domain is called FFT (**Fast Fourier Transform).**
- ***Spectral analysis*** is simply the examination of the spectrum or frequency domain computed from the waveform [2]. Frequencies with higher amplitudes can easily be correlated with their sources.

Transmission Paths

In real applications, transducers are usually installed on the housing of gearboxes or bearings to acquire vibration signals [2]. The vibrations inside a gearbox go through different transmission paths to reach the transducer [2]. Transmission path effect is modeled into two parts: one from gearbox to the casing, and the other part along the casing to the transducer position [2]. Larger the gearbox, higher is the effect of different transmission paths. Transmission path analysis tells us about the characteristics of vibration sources and the best position to locate the sensor on the gearbox.

6

MFS EXPERIMENTAL SET-UP & METHODOLOGY

OBJECTIVES:

- *To perform the condition monitoring and fault diagnosis of bevel gears (healthy, chipped-tooth and broken-tooth gears).*
- *To analyze the effects of frequency, axes, loading and transmission paths via vibration monitoring.*

Methodology

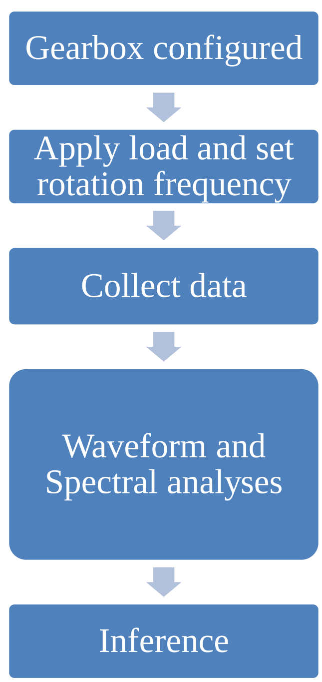

Figure 6.1: Methodology

Experimental Set-up:

- **A Machinery Fault Simulator™:** The Machinery Fault Simulator is designed to study the signature of common machinery faults, such as unbalance, alignment, resonance bearing, crack, gearbox, belt drive etc. We have used MFS to study the faults in the gearbox.

- **One good right-angle gearbox**

- **One worn right-angle gearbox**

- **A healthy/faulty pinion-gear system**

- **Tri-axial Accelerometer and cable(s):** Accelerometer is a device that measures the acceleration of a body in its own instantaneous rest frame. Here we have used a tri- axial accelerometer which measures the acceleration in X, Y and Z axes.

- **One eight-channel DAQ and analysis system:** The use of a data acquisition device is to collect all the major data for further analysis. For our project we have used four, out of eight input modules (X, Y, Z-axis signals and tachometer input).

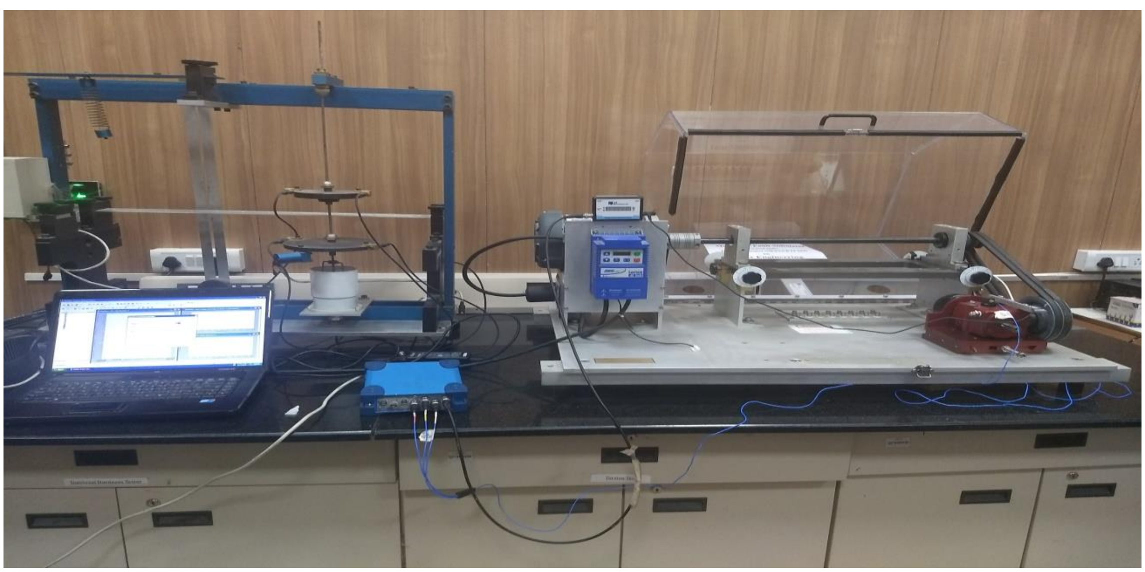

Figure 6.2: Experimental set-up

7
WAVEFORM ANALYSIS

The differences between the basic waveforms of healthy, chipped-tooth, and broken-tooth gear are listed:

X-axis: Time (sec);

Y-axis: Amplitude (m/s^2)

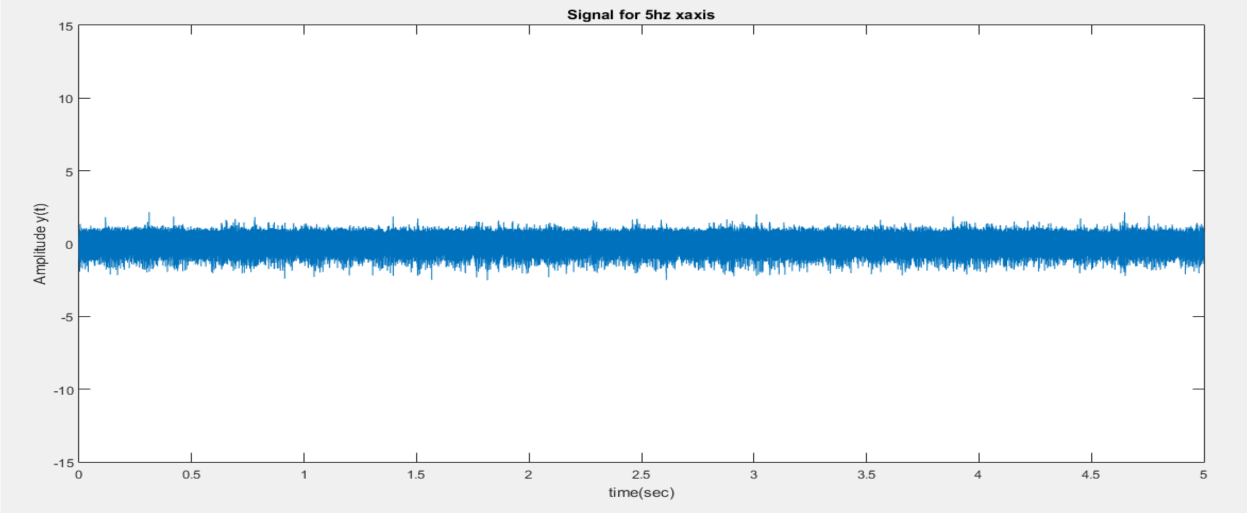

Figure 7.1: 5 Hz Healthy Gear X-axis Waveform

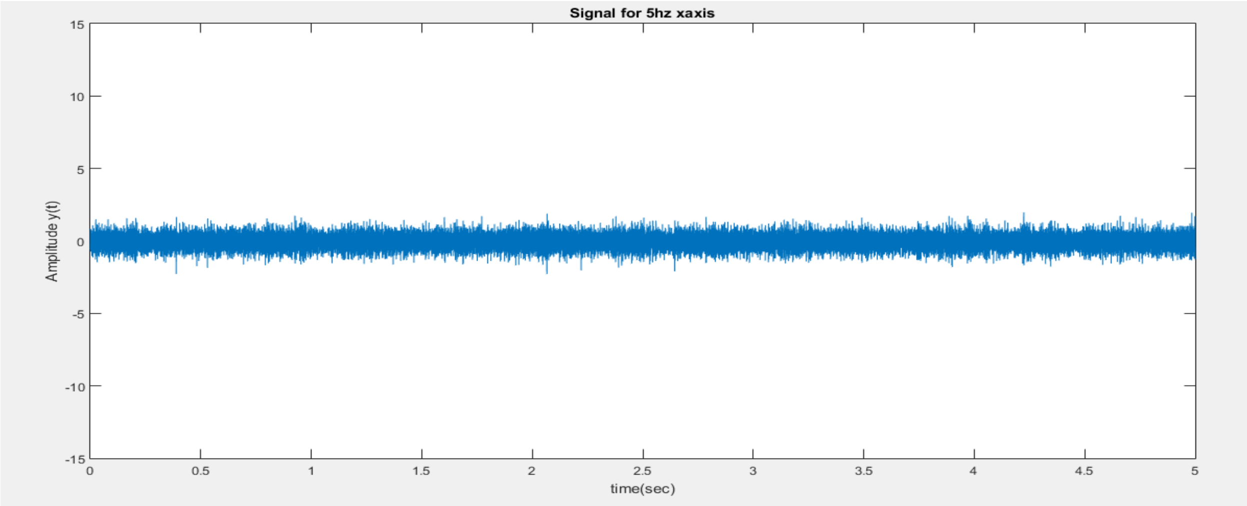

Figure 7.2: 5 Hz Chipped-tooth Gear X-axis Waveform

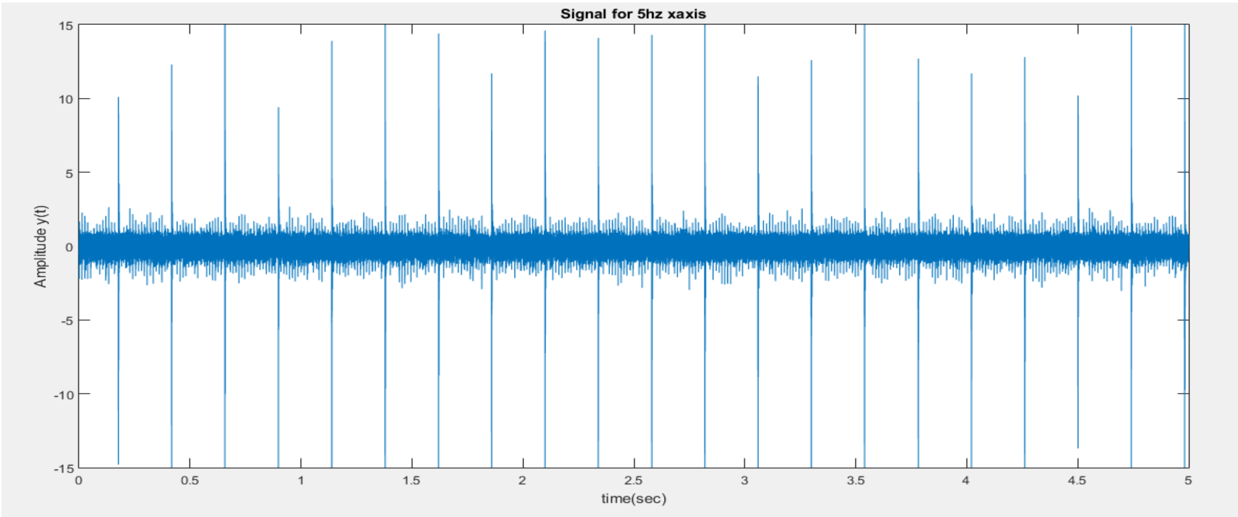

Figure 7.3: 5 Hz Broken-tooth Gear X-axis Waveform

	Healthy Gear	**Chipped-tooth Gear**	**Broken tooth Gear**
Sampling Frequency	2.56x10^4	2.56x10^4	2.56x10^4
Ymax	2.17	1.97	16.2
Ymin	-2.52	-2.29	-18.5
Kurtosis	2.2803	2.9904	124.1993
Inference	No sudden change and lower Kurtosis value.	Frequency of peaks increases and higher Kurtosis value.	Discretely visible peaks and exceptionally high Kurtosis value.

Table 7.1: Waveform Analysis to compare the three Gears

8

SPECTRAL ANALYSIS

Pre-analysis data:

No. of teeth in pinion = 18

No. of teeth in gear = 27

Gear ratio = 3/2

(A) Frequency of motor = 5 Hz

- **Pinion Input Frequency** = 1XP = 1.8 Hz
- **Gear Mesh Frequency (GMF)** = 1.8 x 18 = 32.4 Hz
- **Gear frequency** = 1X = 1.8 x 2/3 = 1.2 Hz

(B) Frequency of motor = 15 Hz

- **Pinion Input Frequency** = 1XP = 5.8 Hz
- **Gear Mesh Frequency (GMF)** = 5.8 x 18 = 105.67 Hz
- **Gear frequency** = 1X = 5.8 x 2/3 = 3.87 Hz

Orientation of axes

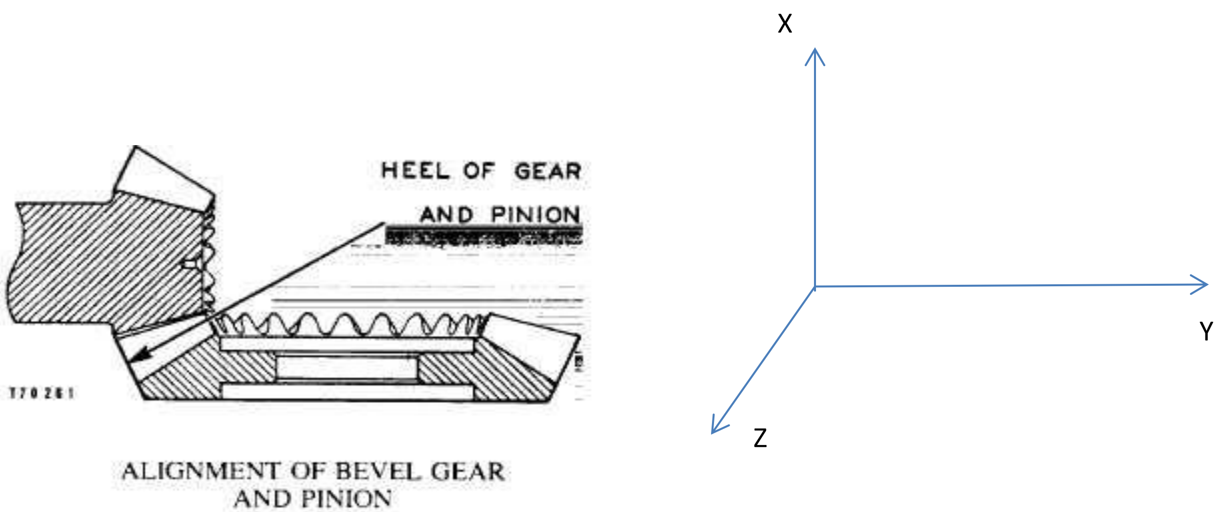

Figure 8.1: Orientation of axes with respect to pinion-gear system.

8.1 ANALYSIS FOR MOTOR FREQUENCY = 5 Hz

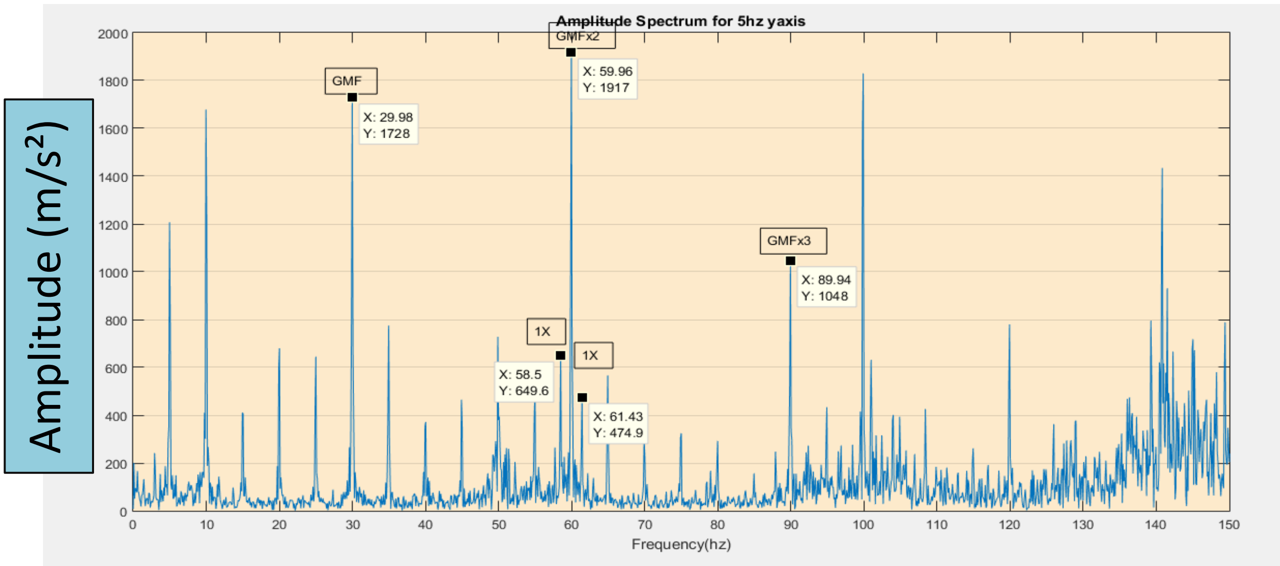

Figure 8.2: 5 Hz No Load Healthy Gear Spectrum

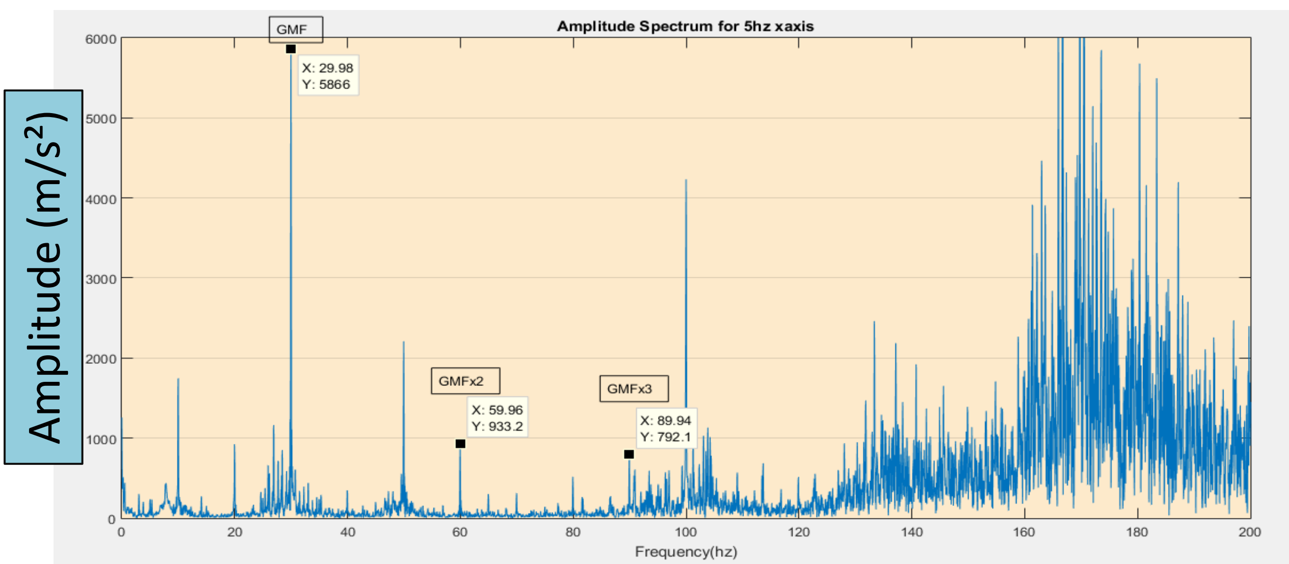

Figure 8.3: 5 Hz No Load Chipped-tooth Gear Spectrum

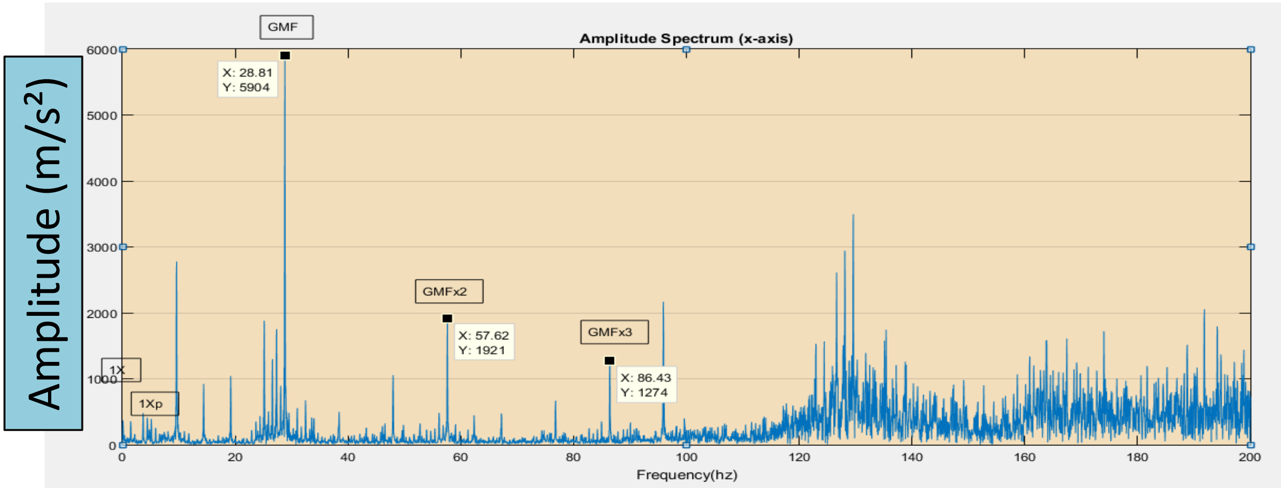

Figure 8.4: 5 Hz No Load Broken-tooth Gear Spectrum

COMPARISON BETWEEN GEARS FOR DIFFERENT AXES

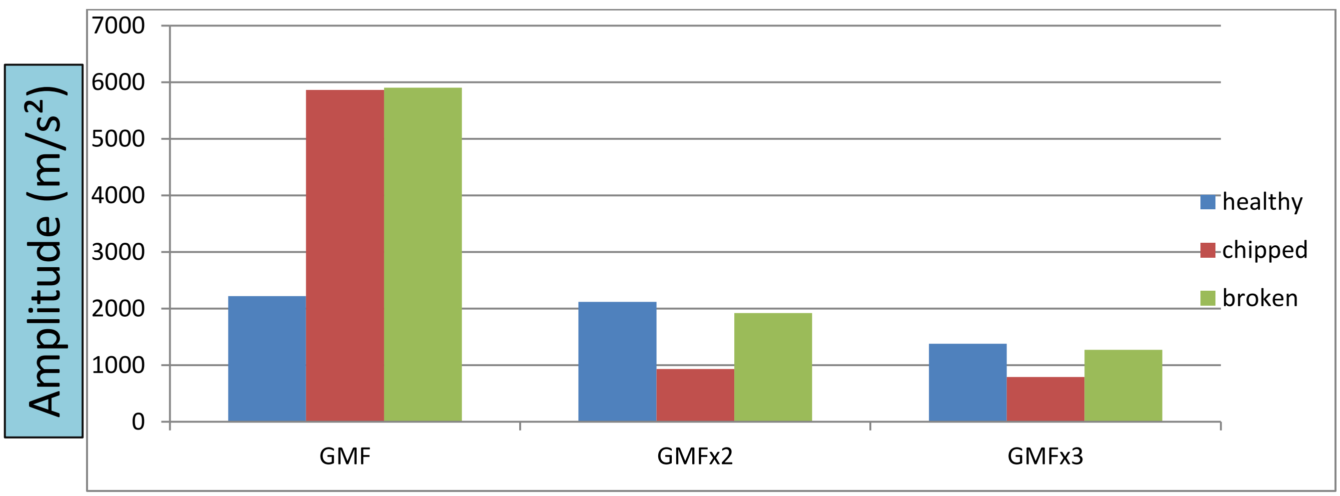

Figure 8.5: 5 Hz No Load X-axis Gear-comparison

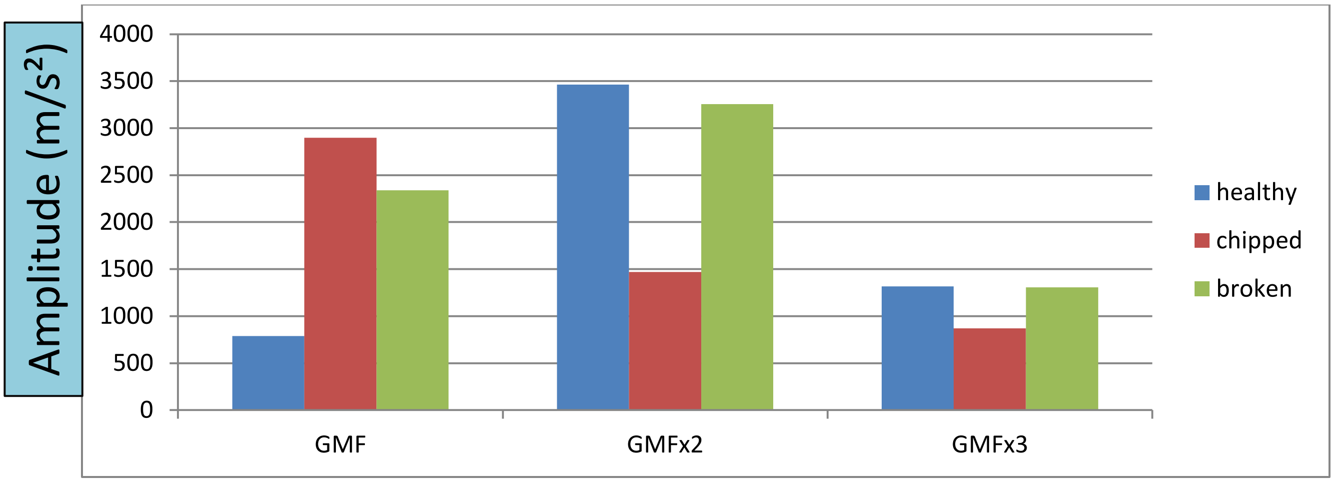

Figure 8.6: 5 Hz No Load Y-axis Gear-comparison

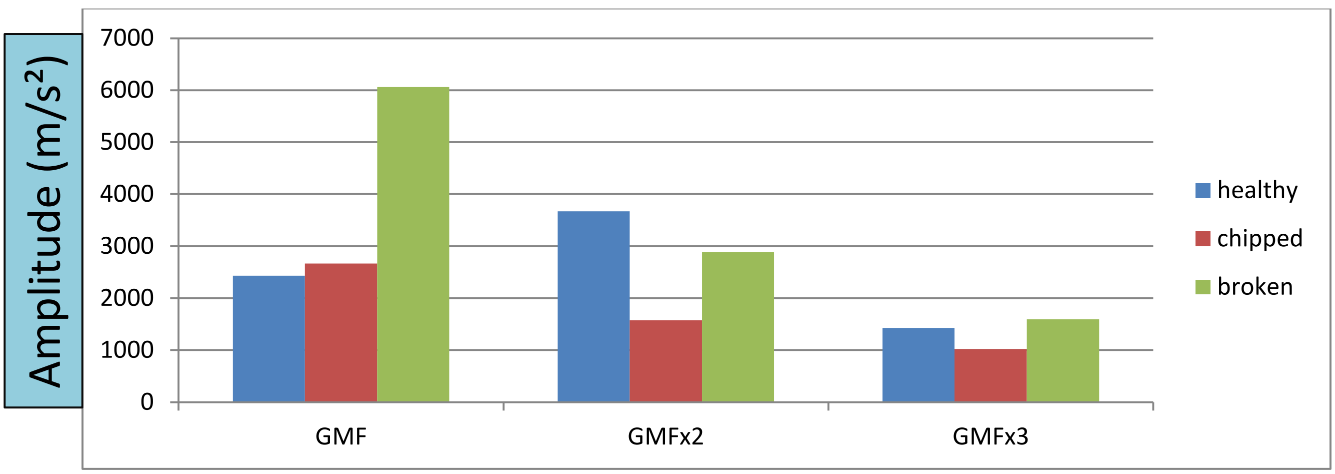

Figure 8.7: 5 Hz No Load Z-axis Gear-comparison

INFERENCE

- The maximum amplitude is obtained at GMFx2 for healthy gear. For the faulty (chipped and broken) gears, it is obtained at GMFx1.
- **The GMF amplitude for healthy gear is less than that for the chipped and broken gears.**

8.2 EFFECT OF MOTOR SPEED

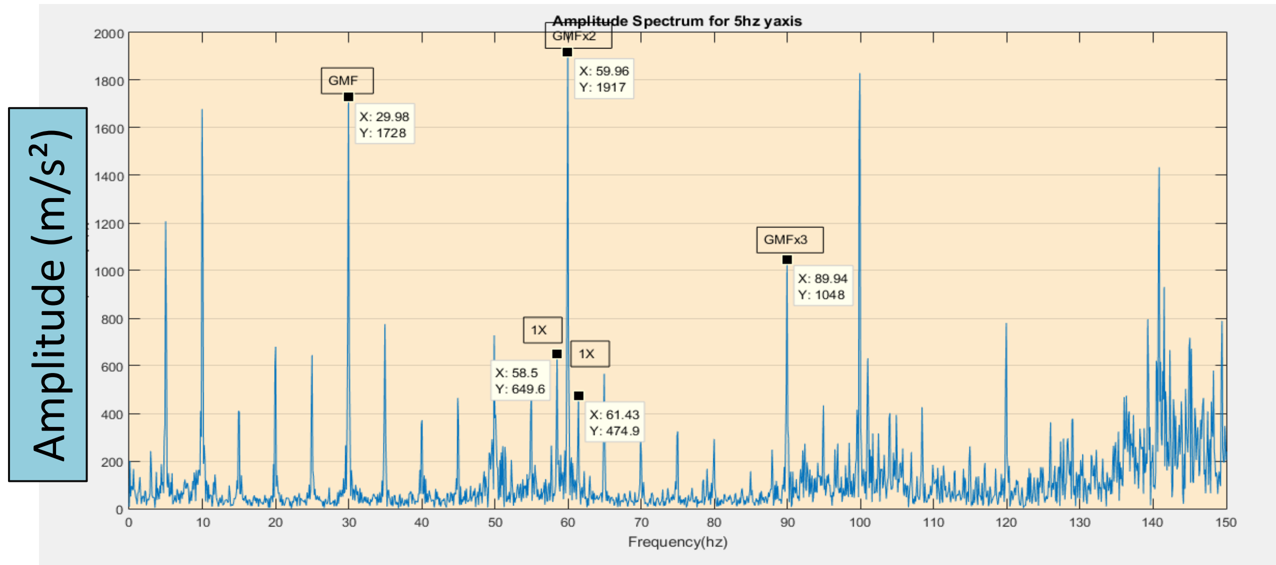

Figure 8.8: 5 Hz No Load Y-axis Spectrum

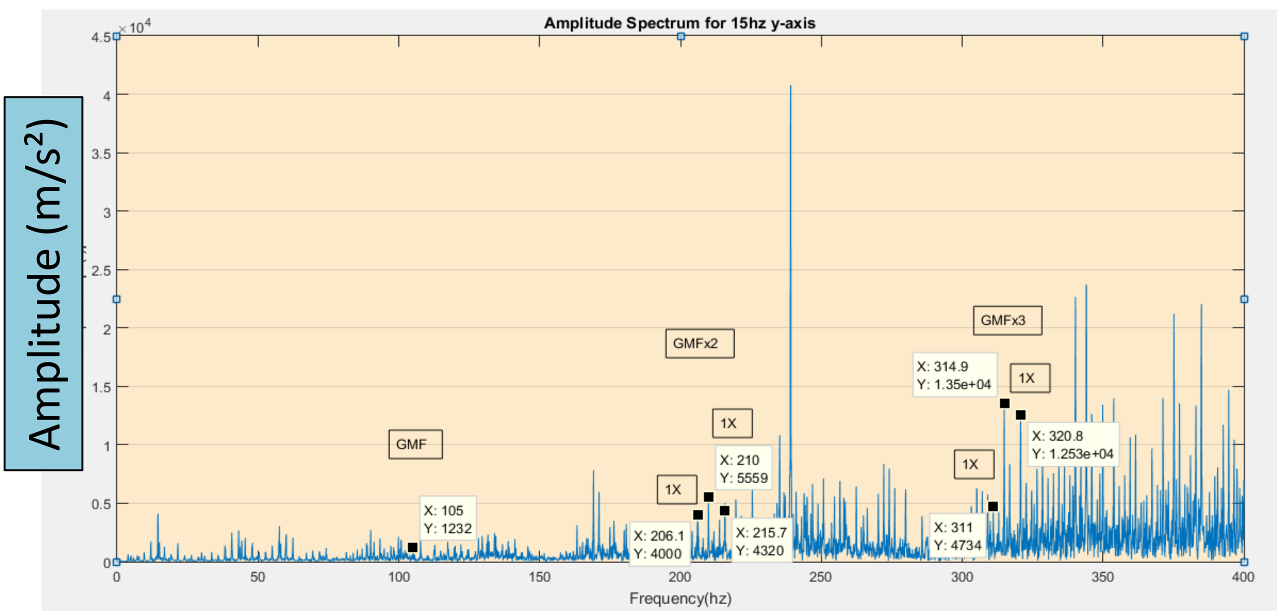

Figure 8.9: 15 Hz No Load Y-axis Spectrum

COMPARISON BETWEEN GEARS AT VARIOUS MOTOR SPEEDS ALONG DIFFERENT AXES

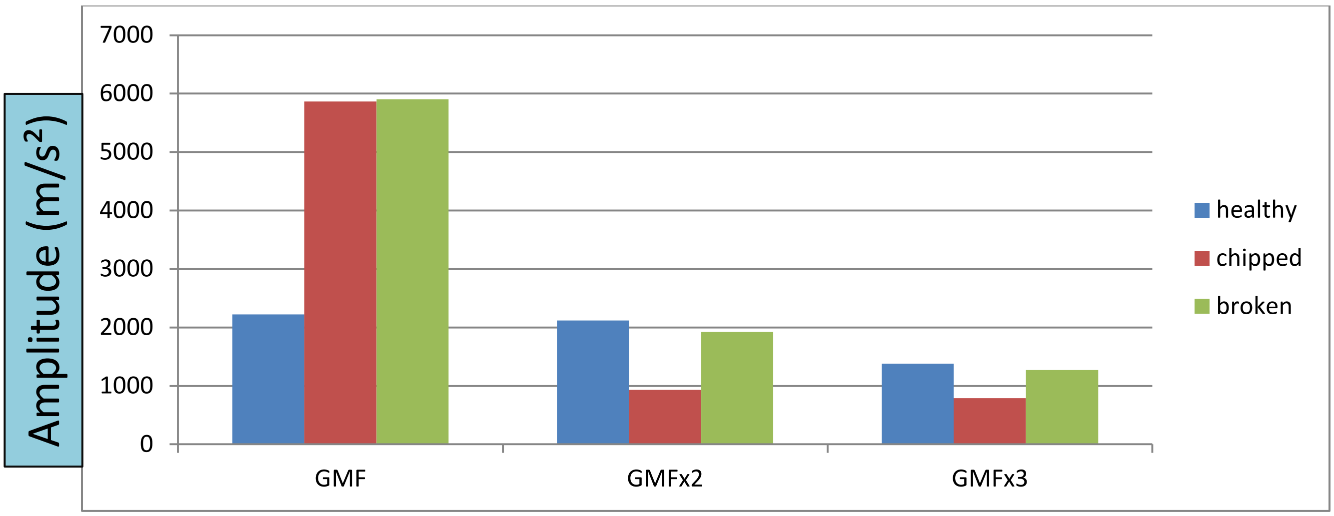

Figure 8.10: 5 Hz No Load X-axis

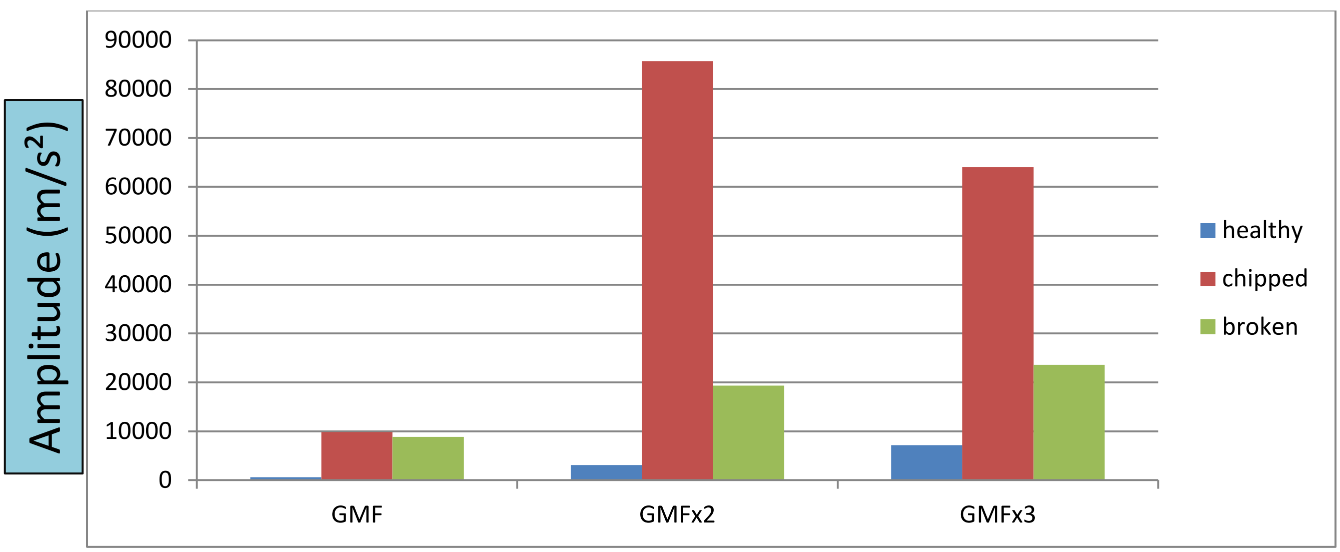

Figure 8.11: 15 Hz No Load X-axis

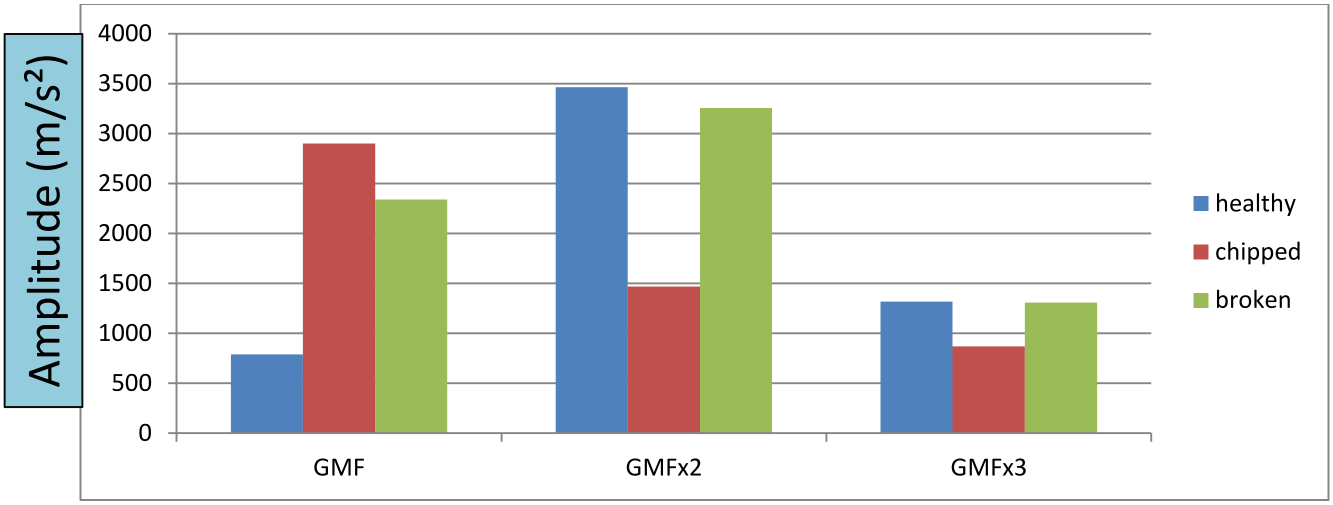

Figure 8.12: 5 Hz No Load Y-axis

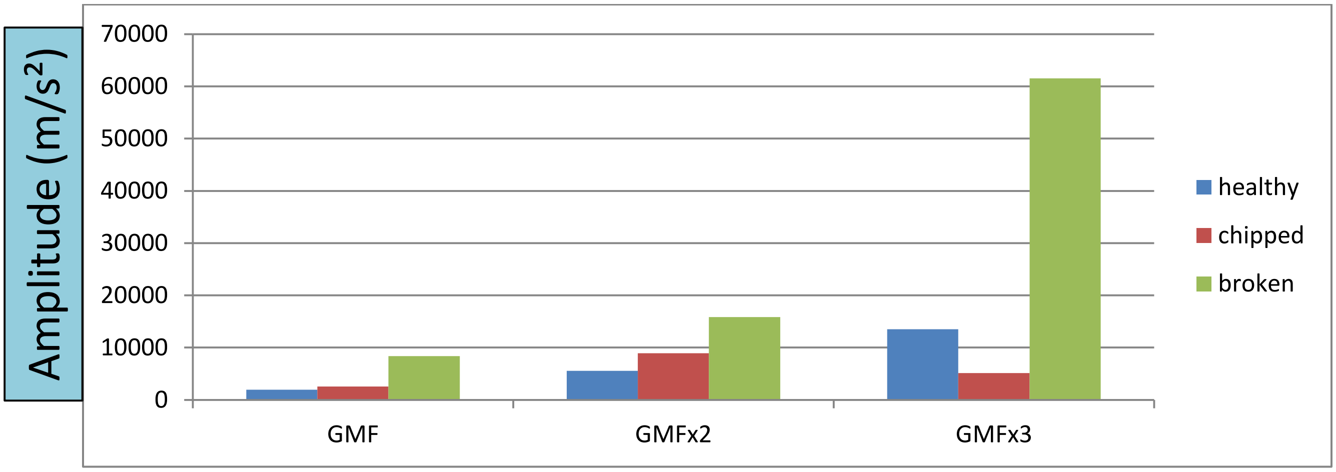

Figure 8.13: 15 Hz No Load Y-axis

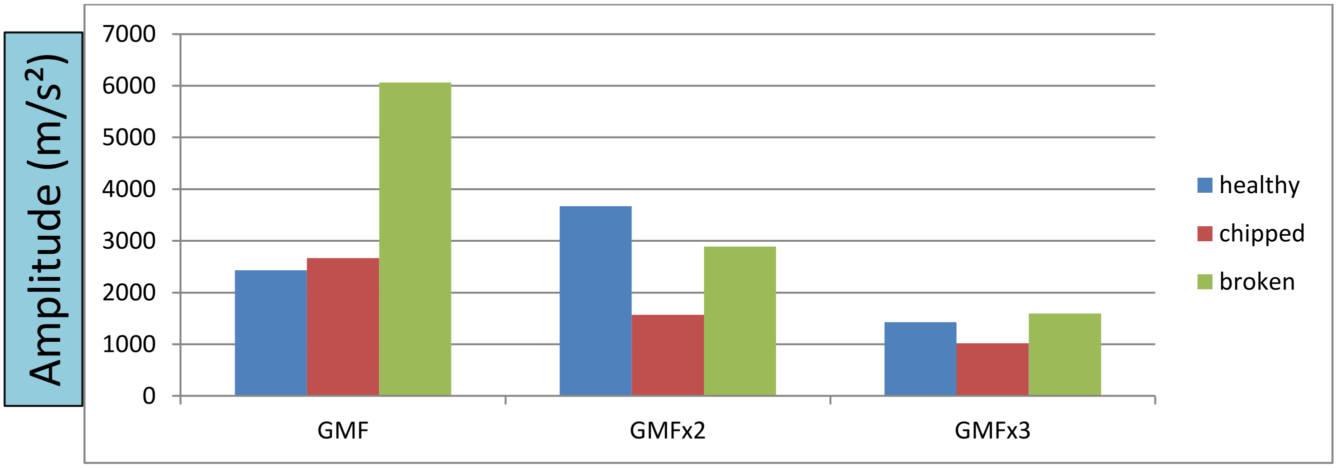

Figure 8.14: 5 Hz No Load Z-axis

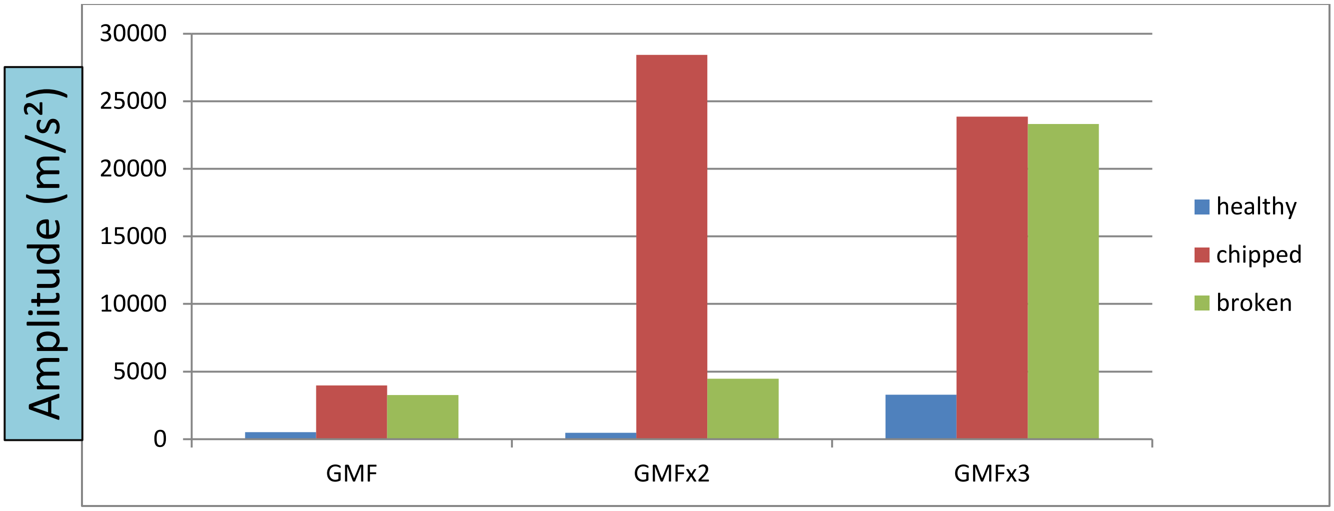

Figure 8.15: 15 Hz No Load Z-axis

INFERENCE

As the motor speed is increased to 15Hz:

- The sidebands increase.
- The overall magnitude of vibration signals increase.
- As was the case at 5 Hz, the GMF amplitude of healthy gear is less than that of the chipped and broken gears.

On increasing motor speed, following changes take place for various gears:

Amplitude at	HEALTHY GEAR	CHIPPED-TOOTH GEAR	BROKEN-TOOTH GEAR
GMF	-	Increases	Increases
GMFx2	-	Increases	Increases
GMFx3	Increases	Increases	Increases

Table 8.1: Effect of increasing speed of motor on various amplitudes

8.3 INTER-AXIAL ANALYSIS

<u>COMPARISON BETWEEN DIFFERENT AXES FOR DIFFERENT CONDITIONS</u>

<u>1st Location:</u> Normal position to locate the sensor.

<u>2nd Location:</u> Displacement of sensor along the X-axis towards the point of contact of the gears.

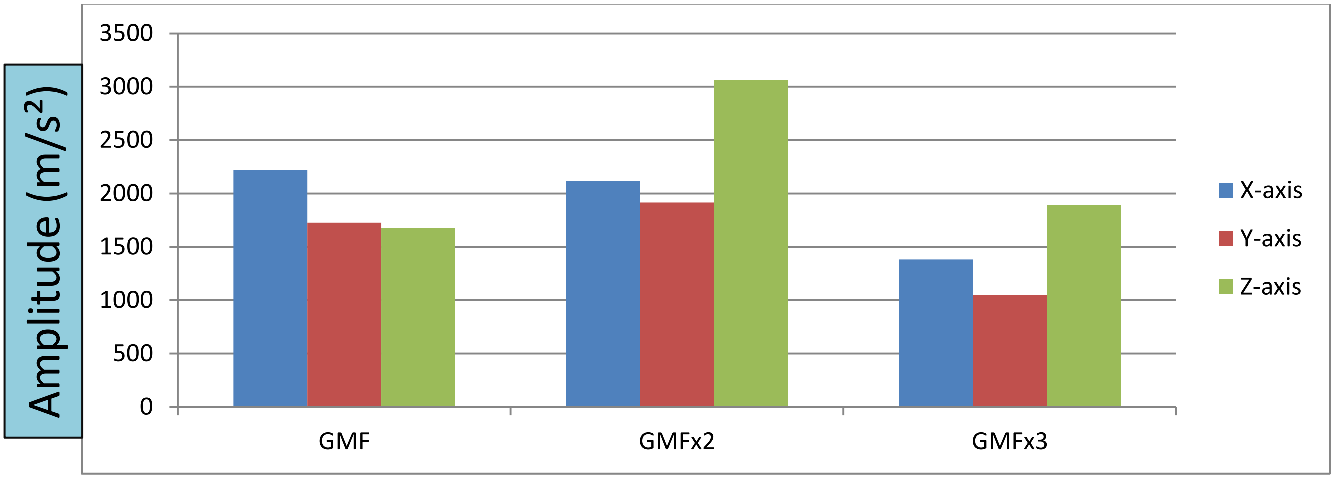

Figure 8.16: 5 Hz No Load 1st Location

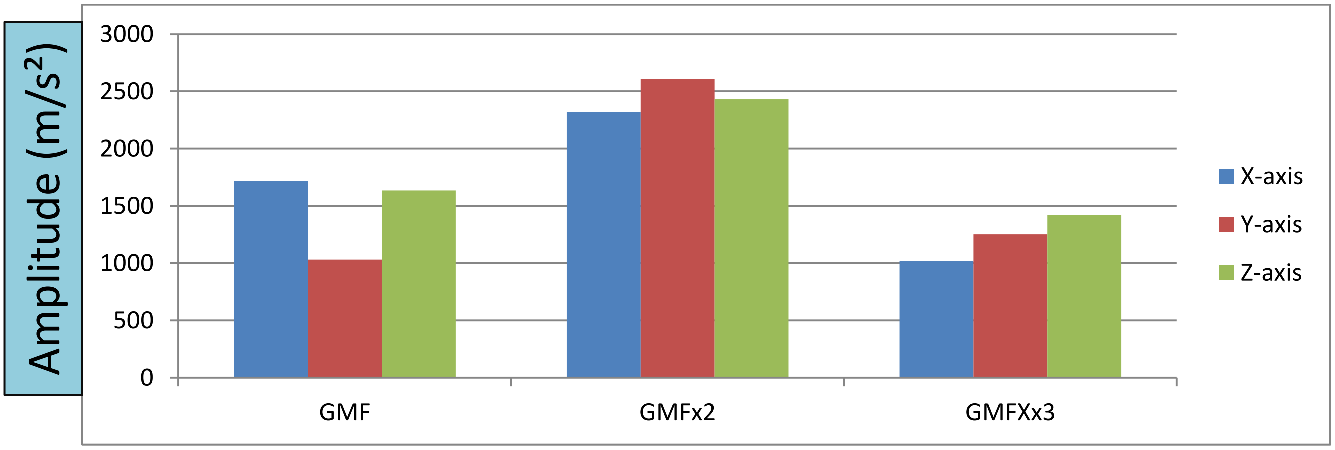

Figure 8.17: 5 Hz 2nd Torque Setting 1st Location

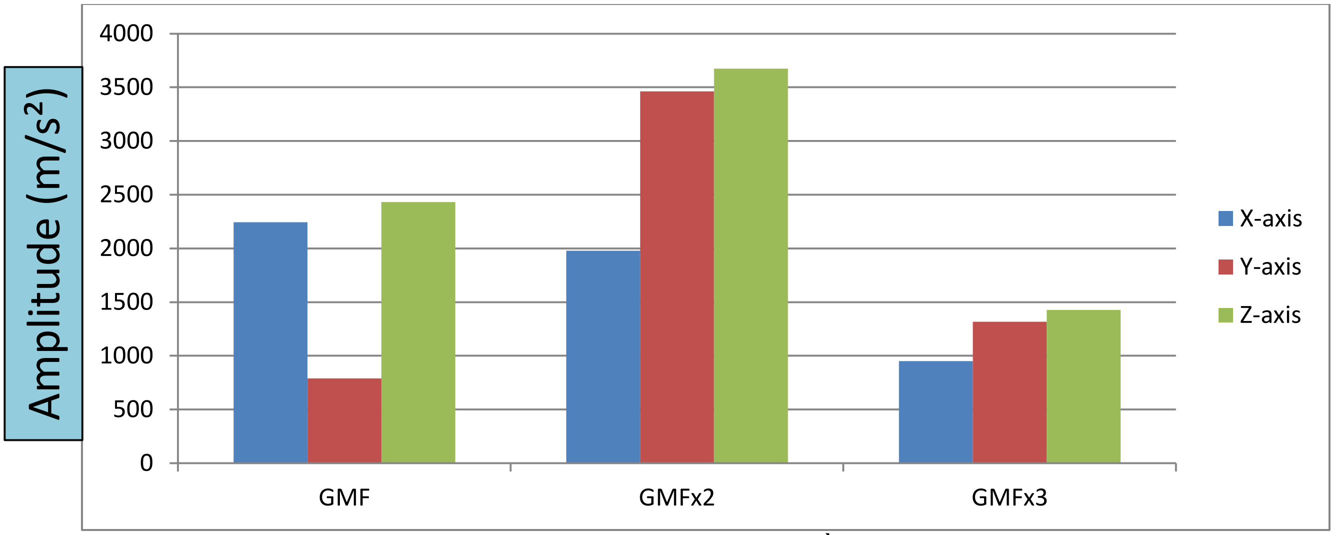

Figure 8.18: 5 Hz No Load 2nd Location

INFERENCE

- Of the 9 bar-comparisons, the maximum amplitude is obtained for Z-axis in 6 of them.
- The other 3 serve as exceptions owing to experimental variations.
- Z-axis is the axis perpendicular to the plane formed by the axes of rotation of the gears.
- Thus, maximum amplitude of vibrations at gear mesh frequencies is obtained along this axis.

8.4 INTER-LOAD ANALYSIS

COMPARISON BETWEEN NO LOAD AND 2ND TORQUE SETTING AT DIFFERENT MOTOR SPEEDS FOR VARIOUS GEARS

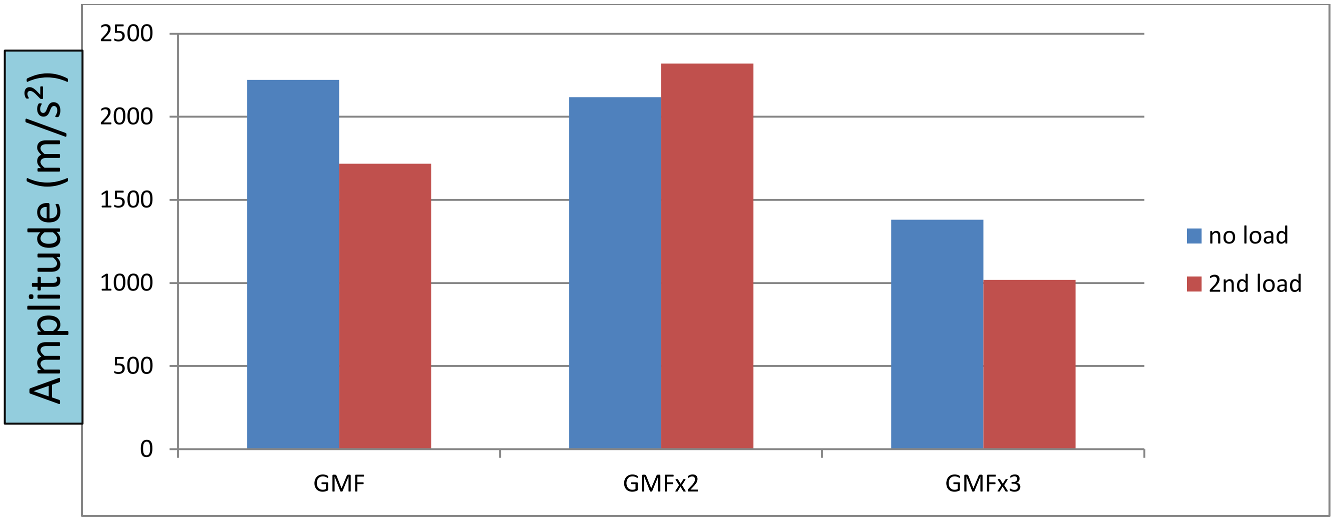

Figure 8.19: 5 Hz Healthy Gear

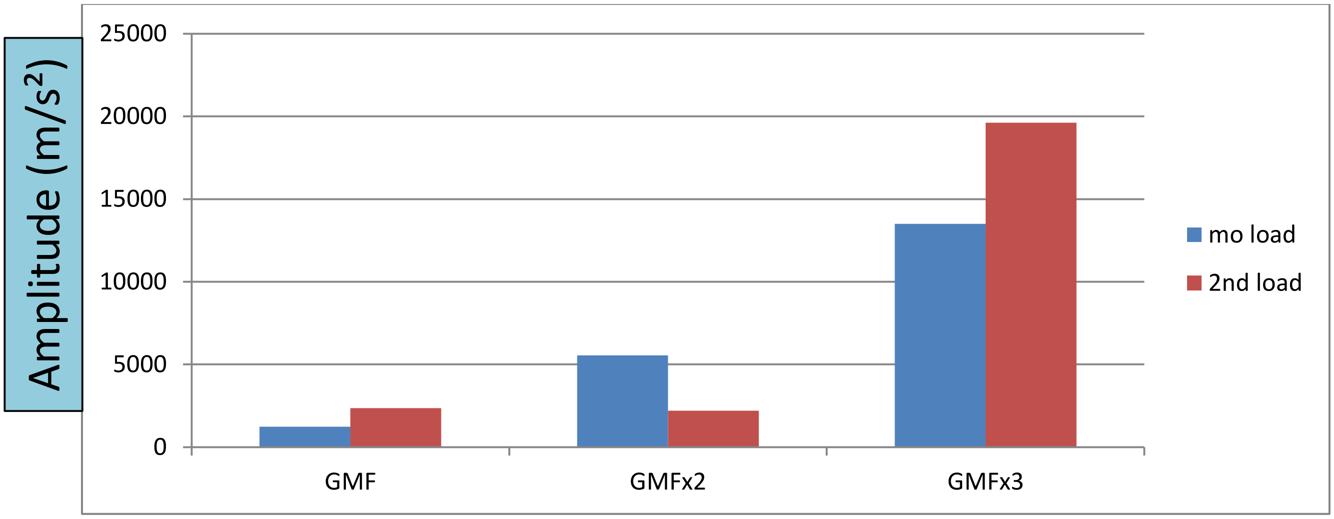

Figure 8.20: 15 Hz Healthy Gear

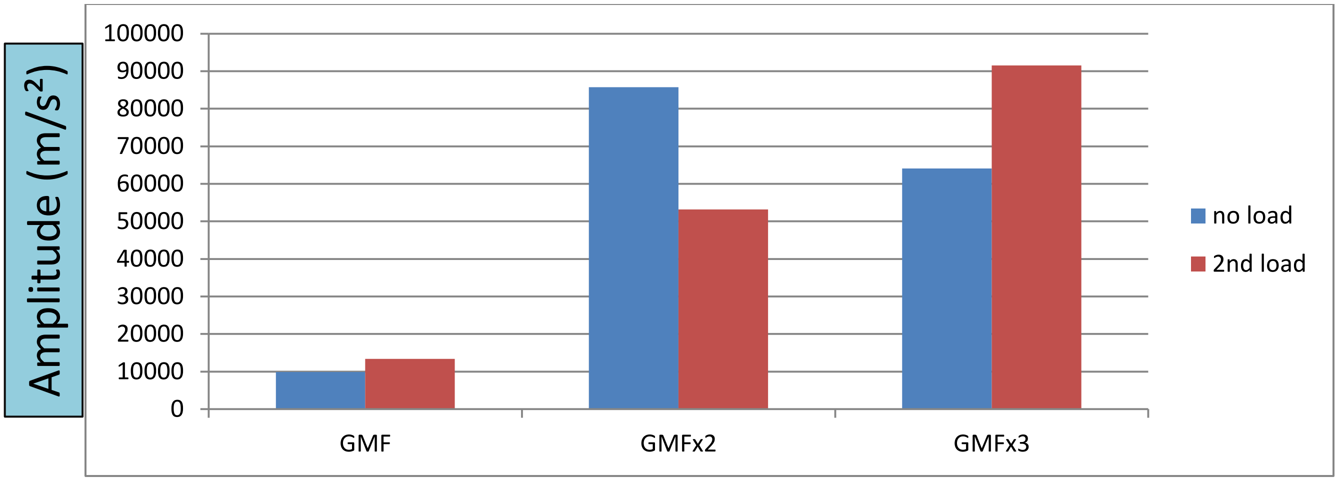

Figure 8.21: 5 Hz Chipped-tooth Gear

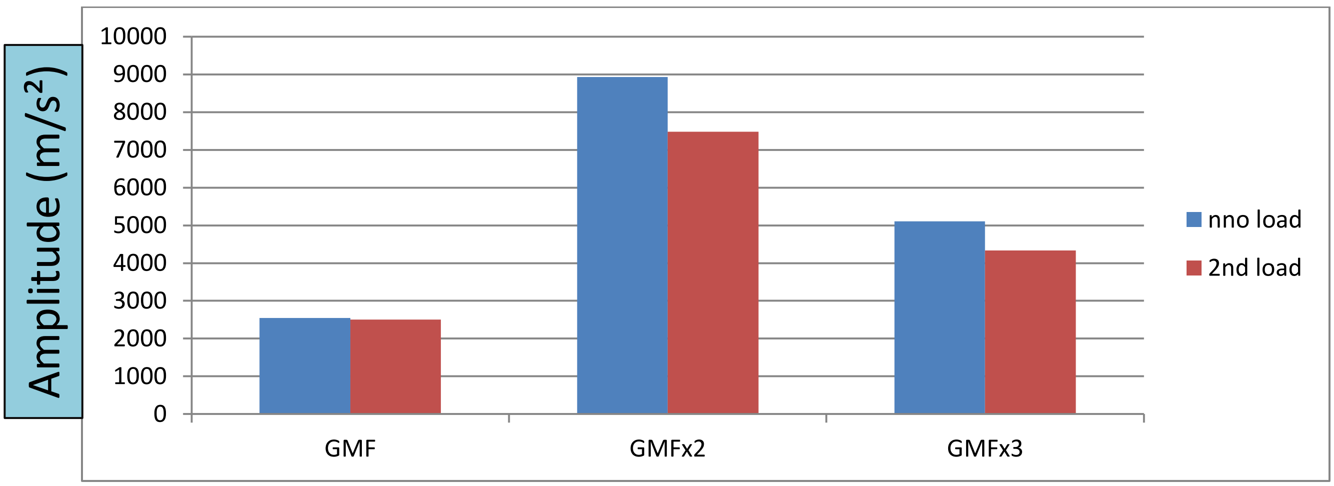

Figure 8.22: 15 Hz Chipped-tooth Gear

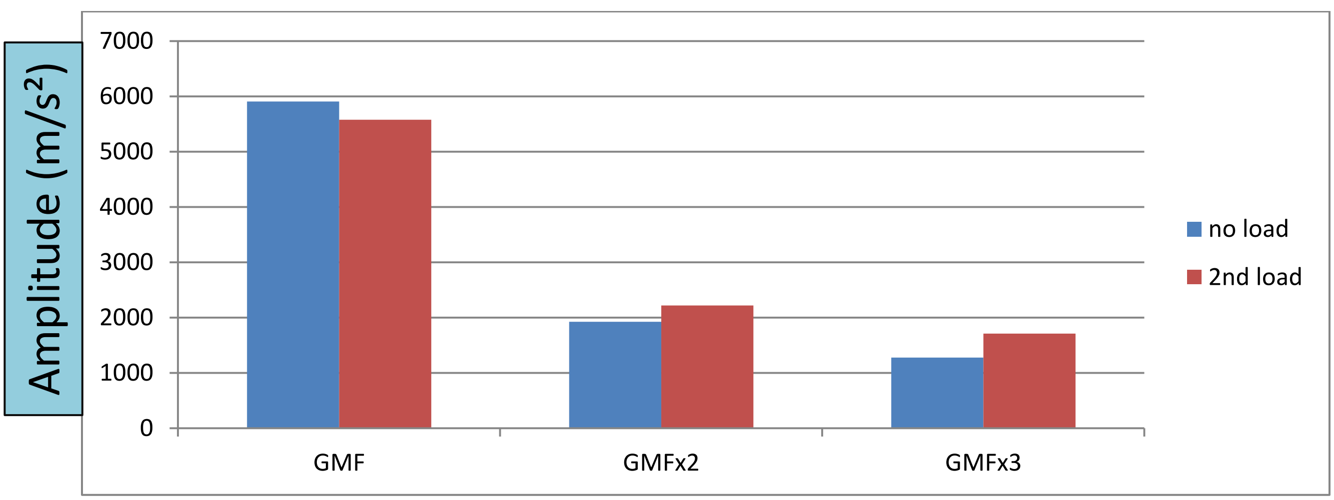

Figure 8.23: 5 Hz Broken-tooth Gear

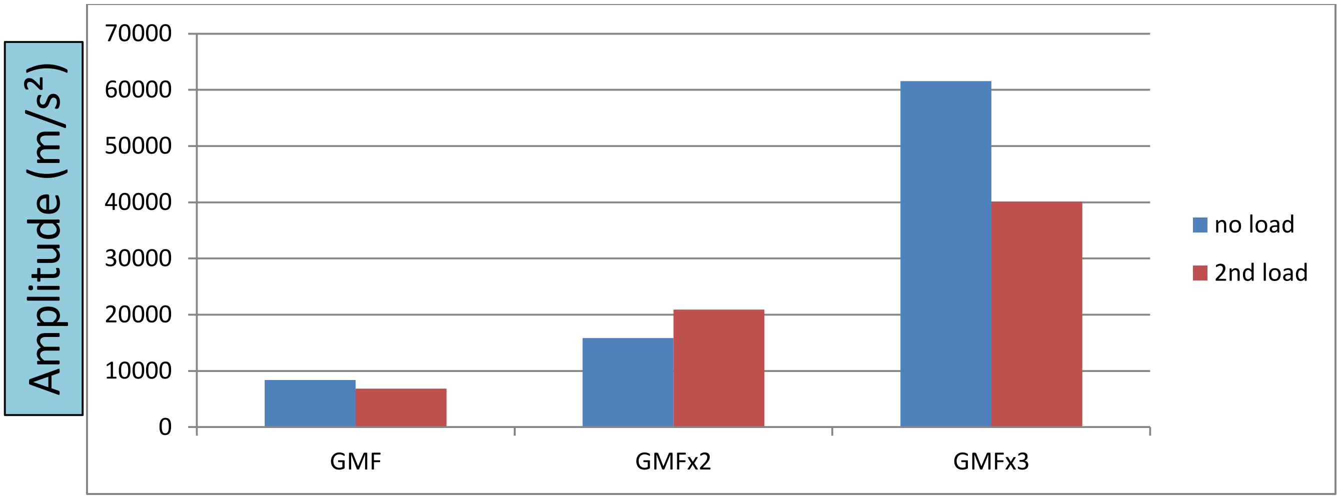

Figure 8.24: 15 Hz Broken-tooth Gear

- On applying torque, following changes take place:

Amplitude at	Healthy	Chipped	Broken
GMF	-	-	Decreases
GMFx2	-	Decreases	Increases
GMFx3	-	-	-

Table 8.2: Effect of application of Torque on various amplitudes

- No noteworthy change in sidebands or GMF amplitude.

The application of load/torque does not affect fault diagnosis to a great extent.

8.5 TRANSMISSION PATH ANALYSIS

The sensor is moved towards the point of contact of the gears along the X-axis.

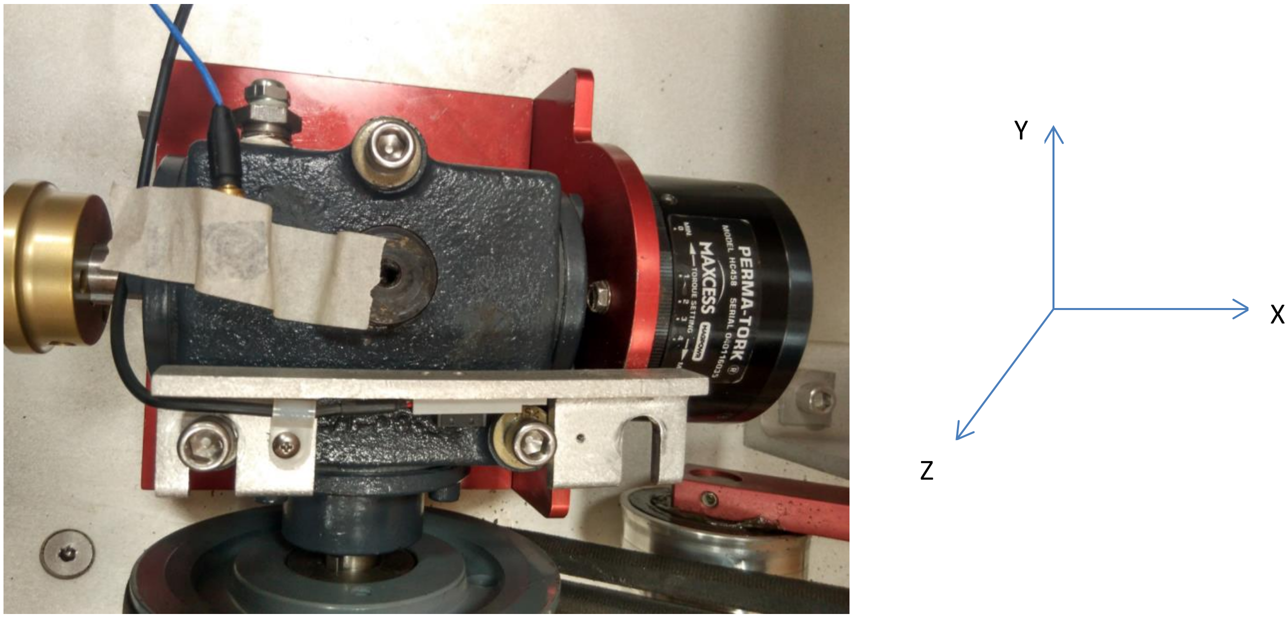

Figure 8.25: Displacement of sensor along the X-axis on the gearbox

SPECTRUMS FOR HEALTHY GEAR AT DIFFERENT LOCATIONS

1st Location: Normal position to locate the sensor.

2nd Location: Displacement of sensor along the X-axis towards the point of contact of the gears.

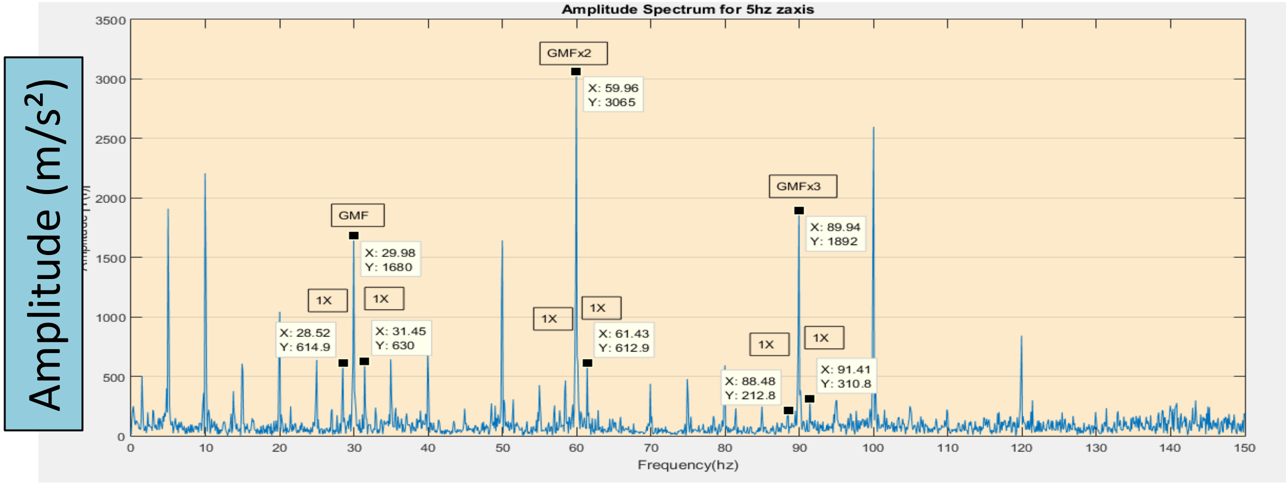

Figure 8.26: Healthy Gear 5 Hz Z-axis 1st Location Spectrum

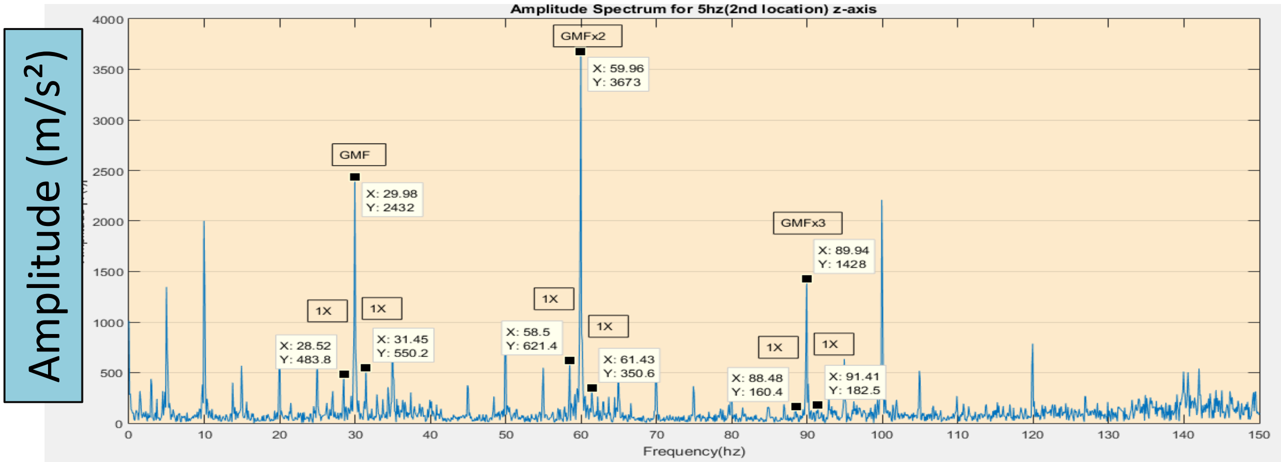

Figure 8.27: Healthy Gear 5 Hz Z-axis 2nd Location Spectrum

COMPARISONS BETWEEN DIFFERENT LOCATIONS FOR THE GEARS

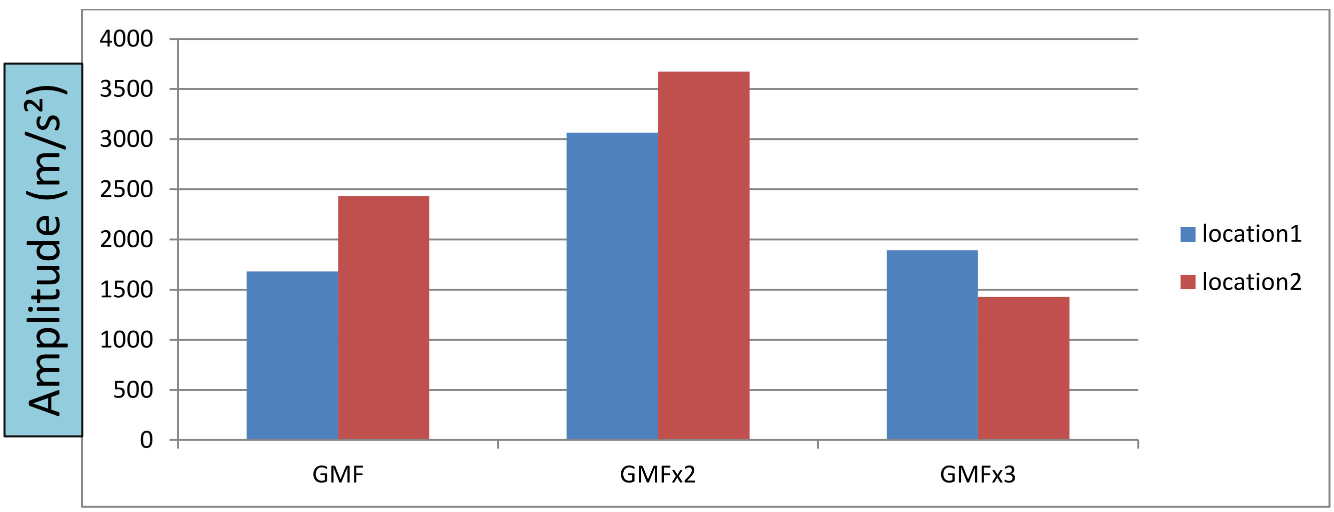

Figure 8.28: Healthy Gear 5 Hz Z-axis

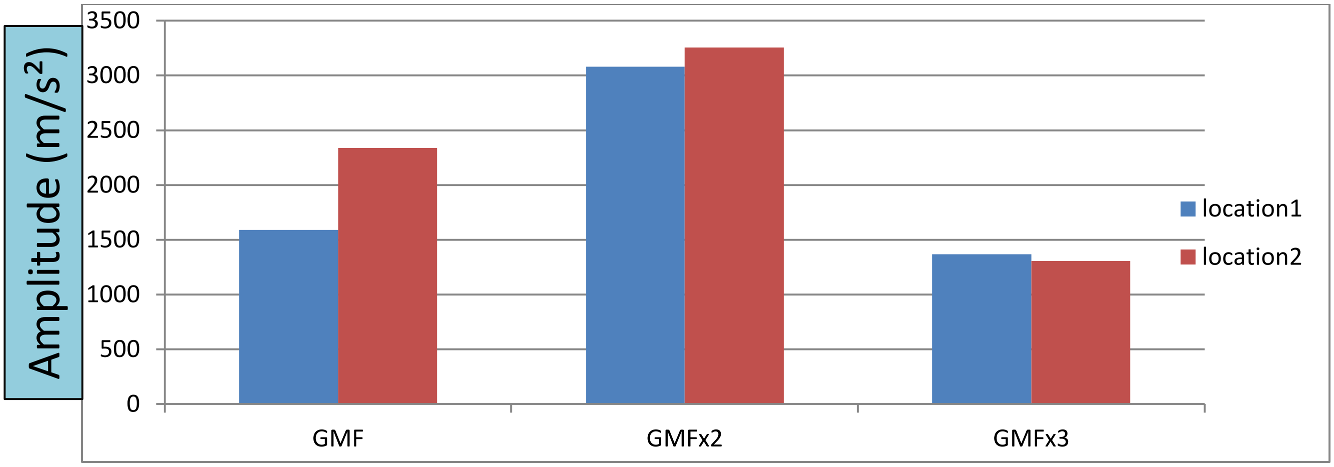

Figure 8.29: Broken-tooth Gear 5 Hz Z-axis

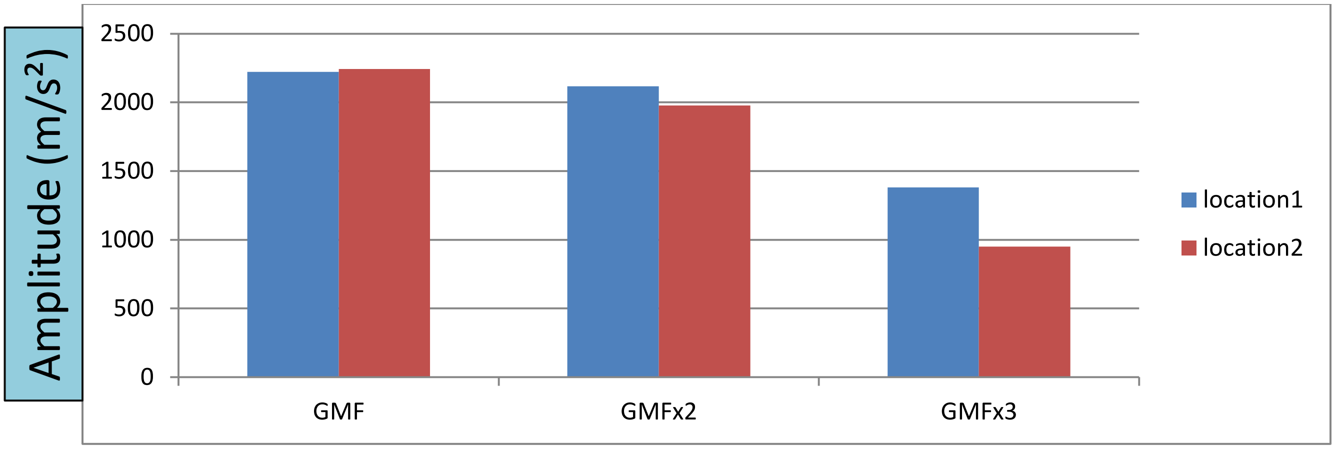

Figure 8.30: Healthy Gear 5 Hz X-axis

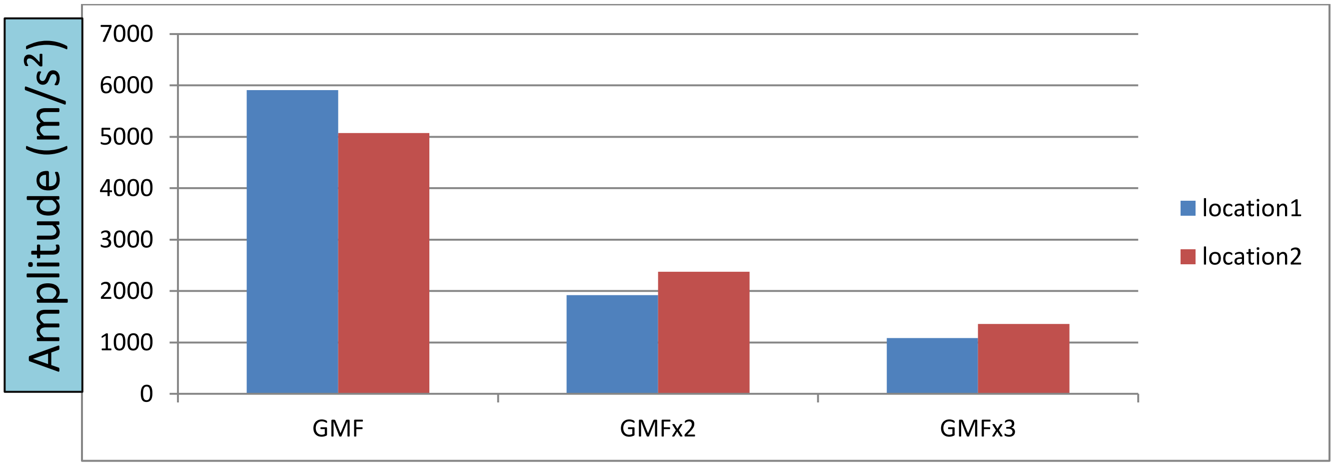

Figure 8.31: Broken-tooth Gear 5 Hz X-axis

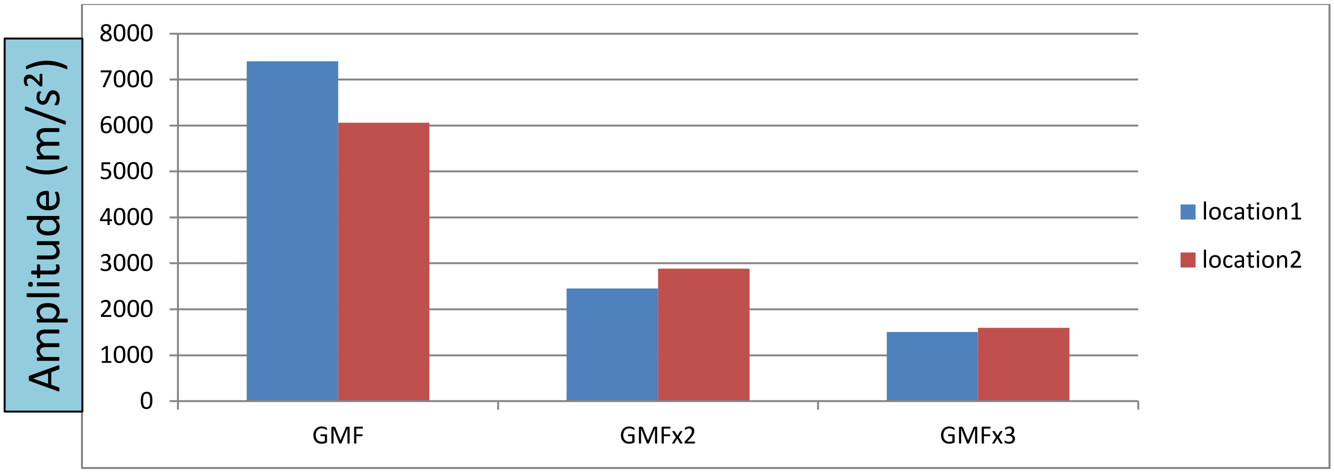

Figure 8.32: Healthy Gear 5 Hz Y-axis

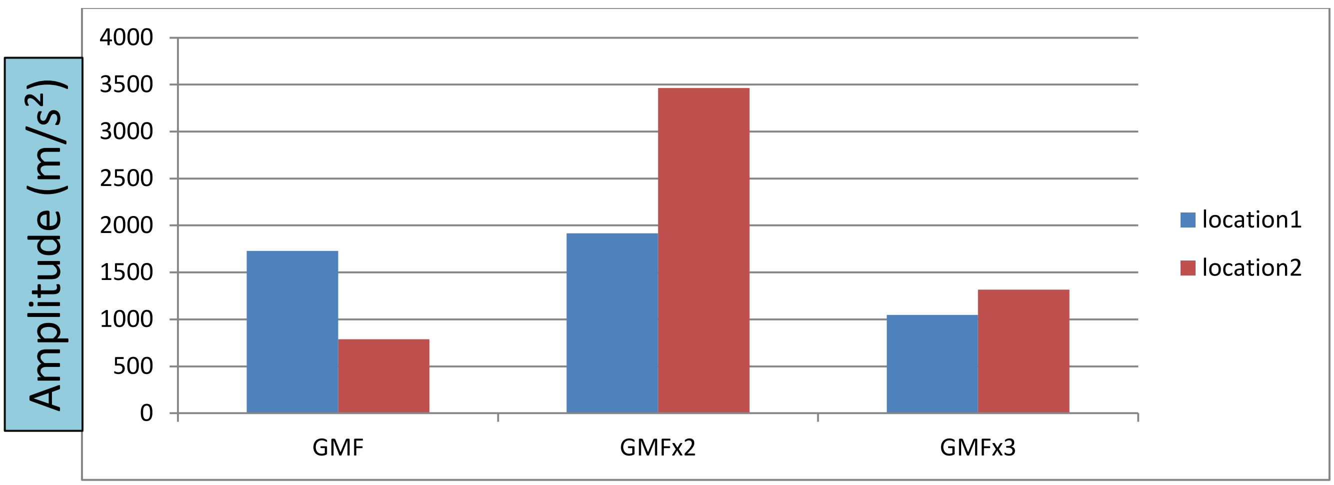

Figure 8.33: Broken-tooth Gear 5 Hz Y-axis

INFERENCE

- There is no noteworthy change in GMF amplitude along X-axis.
- The GMF amplitude along Y-axis decreases.
- The GMF amplitude along Z-axis increases.
- Sidebands amplitude along Z-axis decrease.

Thus, the sensor should be placed as close to the mating gears as possible so as to optimize the magnitudes along the axis perpendicular to the axes of rotation of the gears.

Amplitude at	**X-axis**	**Y-axis**	**Z-axis**
GMF	-	Decreases	Increases
GMFx2	-	Increases	Increases
GMFx3	-	-	Decreases

Table 8.3: Effect of Transmission path on various amplitudes

9

CONCLUSION

From the observations and analyses, we conclude that

- Time signal for healthy gear is a smooth graph.
- Time signal for chipped teeth gear shows frequent peaks at regular intervals.
- Time signal for broken teeth gear shows large peaks at regular intervals.
- For frequency domain, the amplitude at Gear Mesh Frequency (GMF) of a healthy gear is lower than that of chipped or broken teeth gear.
- For higher motor speed the amplitude of the signals increases rapidly and sidebands are more evident.
- The amplitudes of vibration signals are highest at the Z-axis.
- The best location for a sensor is to install it near the gear teeth meeting point.

10

SCOPE OF THE PROJECT

It is the most popular condition monitoring technique. The knowledge of it is benificial to many industries.

- The knowledge of Vibration Monitoring is helpful in detecting even minor errors in various parts of a machine during operation as it is a highly sensitive technique.
- This project finds its scope in increasing the efficiency of a geared machine by predicting the defects in it with the help of waveform and spectral analyses. It also helps avoiding any major catastrophe.
- Varying speed and power systems, such as automobiles can be easily dealt with the use of frequency and load analyses.
- The inter-axial analysis is helpful when using uniaxial accelerometer.
- Transmission Path analysis tells us the best position to locate the sensor on the gear box.

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