Analysis of Noise and Vibrations of Helical Gears Finished by Abrasive Flow Finishing

M.Tech. Thesis

by

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Discipline of Mechanical Engineering

Indian Institute of Technology Indore

July 2018

Analysis of Noise and Vibrations of Helical Gears Finished by Abrasive Flow Finishing

A Thesis

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

of

Master of Technology

in

Mechanical Engineering

With specialization in

Production and Industrial Engineering

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Candidate's Declaration

I hereby certify that the work which is being presented in the thesis entitled "**Analysis of Noise and Vibrations of Helical Gears Finished by Abrasive Flow Finishing**" in the partial fulfillment of the requirements for the award of the degree of **Master of Technology** in **Mechanical Engineering** with specialization in **Production and Industrial Engineering** and submitted in the **Discipline of Mechanical Engineering, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from **May 2017 to June 2018** under the supervision of **Prof. Neelesh Kumar Jain** and **Prof. Anand Parey** of Discipline of Mechanical Engineering.

The matter presented in this thesis has not been submitted by me for the award of any degree from any other institute.

Vivek Rana

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

(Prof. Neelesh Kumar Jain) **(Prof. Anand Parey)**

Vivek Rana has successfully completed his M.Tech Oral Examination held on ………...

Signature of M.Tech Thesis Supervisors
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Name and signature of PSPC member 1 with date: **(Prof. Ram Bilas Pachori)**

Name and signature of PSPC member 2 with date: **(Dr. Devendra L. Deshmukh)**

Signature of Chairman, Oral Examination Board with date

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Vivek Rana

Dedicated

to

My Parents

Abstract

Gear is a toothed wheel used in machinery to transmit motion and/or power to perform the intended task. Gears are the main exciter of noise and vibration in all machines wherever used. Vibrations generated due to gear motion are transmitted to surrounding structure and airborne noise is produced. The primary cause of noise and vibration in gears is force variations due to rough surface, microgeometry errors and load variation. Finishing processes play an important role in reducing surface roughness and microgeometry errors. In present research work helical gears made up of 20MnCr5 alloy steel were manufactured by hobbing process and finished by Abrasive Flow Finishing (AFF) using optimum parameters which are extrusion pressure 5Mpa, abrasive mesh size 100 with 30% volumetric concentration, abrasive particles of SiC and finishing time 25 minute. In present research work it was observed that there is reduction in surface roughness, microgeometry errors leading to reduction in noise and vibration levels of the AFF finished helical gear pair. Three parameters of roughness (i.e. average surface roughness 'R_a', maximum surface roughness 'R_{max}', mean roughness depth 'R_z'), four parameters of microgeometry (i.e. total profile error 'F_a', total lead error 'F_b', total pitch error 'F_p' and radial runout 'F_r') and RMS value of overall vibration and vibration at gear mesh frequency were measured before and after finishing of the helical gears.

Table of Contents

List of Figures

List of Tables

Nomenclature

F_a	Total profile error (μm)
F_b	Total lead error (μm)
F_p	Cumulative pitch error (μm)
F_r	Total runout (μm)
R_a	Average surface roughness (μm)
R_z	Mean roughness depth (μm)
R_{max}	Maximum roughness depth (μm)
ϕ	Pressure angle of the involute profile (degree)
ψ	Helix angle (degree)
a_x	Acceleration in radial direction (X-axis)
a_y	Acceleration in axial direction (Y-axis)
a_z	Acceleration in tangential direction (Z-axis)
a_r	Resultant acceleration
L_p	Sound pressure level
L_I	Sound intensity level
L_W	Sound power level

Acronyms

AFF	Abrasive Flow Finishing
ECH	Electrochemical Honing
GMF	Gear Mesh Frequency
PIR_a	Percentage Improvement in average surface roughness
PIR_z	Percentage Improvement in mean roughness depth
PIR_{max}	Percentage Improvement in maximum roughness depth
PIR_t	Percentage Improvement in maximum peak to valley depth
PIF_a	Percentage Improvement in total profile error
PIF_b	Percentage Improvement in total lead error
PIF_p	Percentage Improvement in total pitch error
PIF_r	Percentage Improvement in radial runout
RMS	Root Mean Square

Chapter 1

Introduction

1.1 Introduction to Gears

Gear is a toothed wheel used for transfer motion and/or power mechanically with and without a change in the direction and/or speed. Gears constitute an economical and positive drive motion and/or power transmission, particularly when requirements of power or accuracy are high.

1.2 Classification of Gears

Gears can be classified according to different criteria. Most important criteria is the relative position of the shafts on which driving and driven gears are mounted. They can be parallel or intersecting or non-parallel and non-intersecting. Gears mounted on the *parallel shafts* are manufactured from cylindrical blanks therefore they are known as *cylindrical gears*. Spur, single helical, double helical, herringbone gears belong to this category. Gears mounted on the *intersecting shafts* are manufactured from the frustum of conical blanks therefore they are referred as *conical gears*. Straight bevel, spiral bevel, zero bevel, miter gear, and face gear or crown wheel are examples of conical gears. Gears mounted on *non-parallel and non-intersecting shafts* are called as *skew shaft gears*. Hypoid gears, worm and worm wheel, and cross-helical gears belong to this category of gears. Gears can also be classified as circular and non-circular gears according to shape of the gear blank. Non-circular gears are used where speed variations are desired and *sector gears* are used when less than 360 degrees of rotation is desired. Figure 1.1 depicts different types of gears. According to location of teeth, gears can be either internal or external type. According to profile of teeth, gears can be either involute or cycloidal type. Gears can have straight, curved inclined teeth. According to peripheral velocity, gears can be classified as low velocity gears having less 3 m/s; medium velocity of gears (3-15 m/s); or high velocity gears (> 15 m/s). According to major diameter, gears can be micro-sized (< 1 mm) meso-sized (1-10 mm) or macro-sized (> 10 mm).

Cylindrical gears

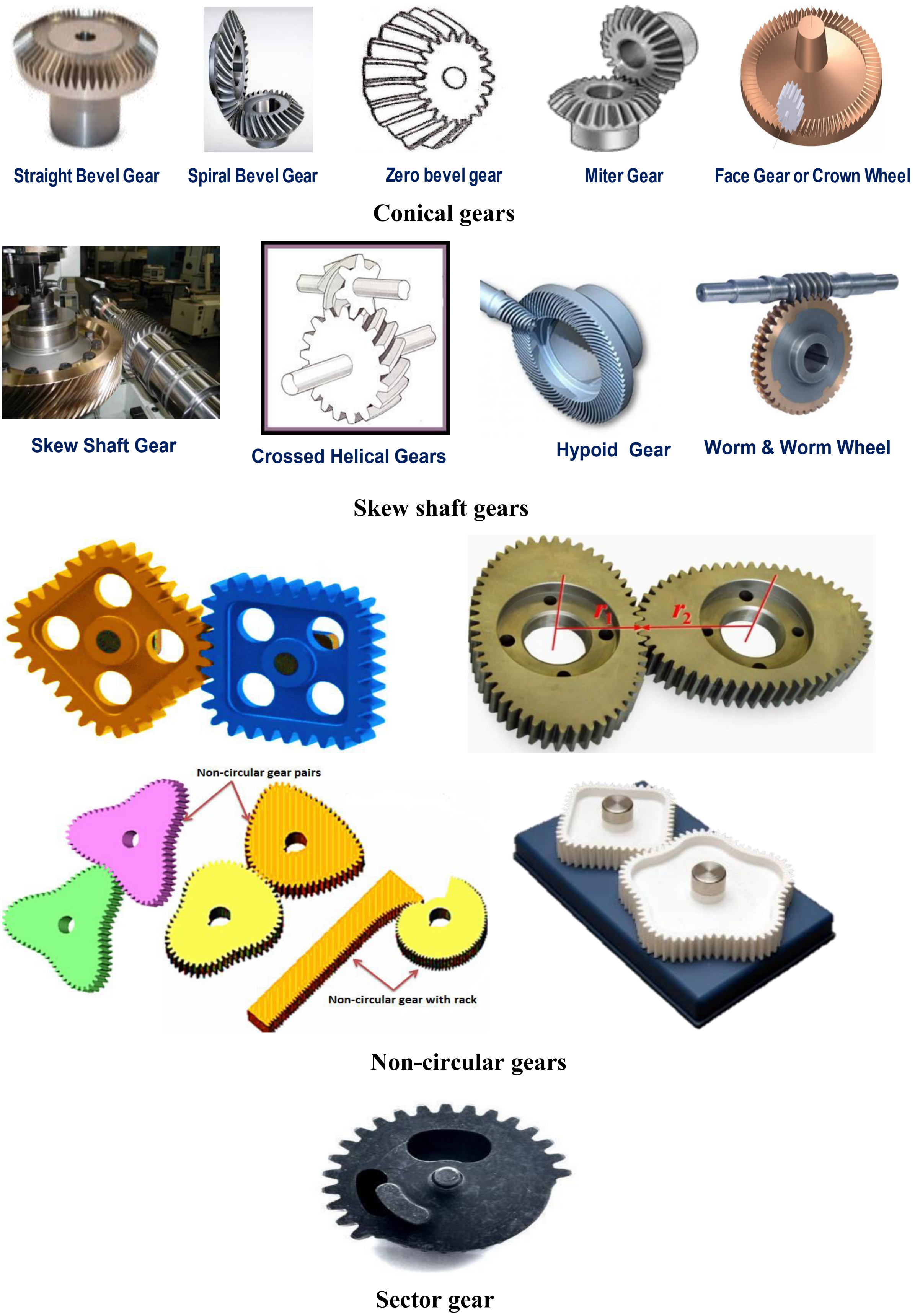


Fig. 1.1: Different types of cylindrical, conical, skew shaft, and non-circular gears.

1.3 Introduction to Helical Gear

The teeth of a helical gear are cut at an angle with respect to the axis of rotation. This angle is known as helix angle. Helical gears which are meshing with each other should have same helix angle but of opposite hand i.e. helical gear left hand helix will mesh with the helical gear having right hand helix. The contact between the meshing helical gears begins from a point on the leading edge of a tooth and gradually extends along the diagonal line across the tooth. Helical gears have the larger contact ratio than the corresponding spur gears therefore, they operates in smoother and quieter manner than a spur gears thus resulting in lesser noise and vibrations. Due to the twist in the tooth trace, single helical gears produce axial thrust force on their mounting shafts. Therefore, it is desirable to use thrust bearings for single helical gears to absorb the axial thrust force. However, combining right hand and left hand helical gears making double helical gears will eliminate the thrust force. This problem is overcome by using double helical gears which have teeth of opposite helix hands (i.e. right and left hands) are cut adjacent to each other as shown in Fig. 1.1.

Manufacturing of double helical gears is very difficult therefore little gap is provided between the teeth having opposite helix angle. These gears called Herringbone gears (shown in Fig. 1.1). However, if there is any error in phasing of right and left teeth arrays or if the helical gears are not meshing correctly then the gear drive creates alternating thrust in the axial direction causing vibrations. For the helical gears, any directional errors in the relative tooth lines between the driver and the driven shafts can be corrected by adjusting the position of the bearings but it is not possible with the herringbone gears. For these reasons, it is recommended to use hardened and ground single helical gears for large gears in the ships. Helical gears are generally parallel shaft gears and their meshing involves almost all rolling contact therefore, their general efficiency is very high (i.e. ranging from 90-99.5%).

1.4 Gear Noise and Vibrations

Noise is an unwanted sound which is unpleasant, loud or disruptive to normal hearing. Noise is indistinguishable from sound because both are vibrations in a medium such as air or water. Distinction happens when the brain receives and perceives a sound.

When the gears operate especially at high loads and speeds then the gear noise and vibration become a big problem. Since, it can happen due to many causes or their combination therefore, it is very difficult to identify the exact cause of gear noise and vibrations. Figure 1.2 shows the significant factors which contribute to the generation of noise and vibrations in gears.

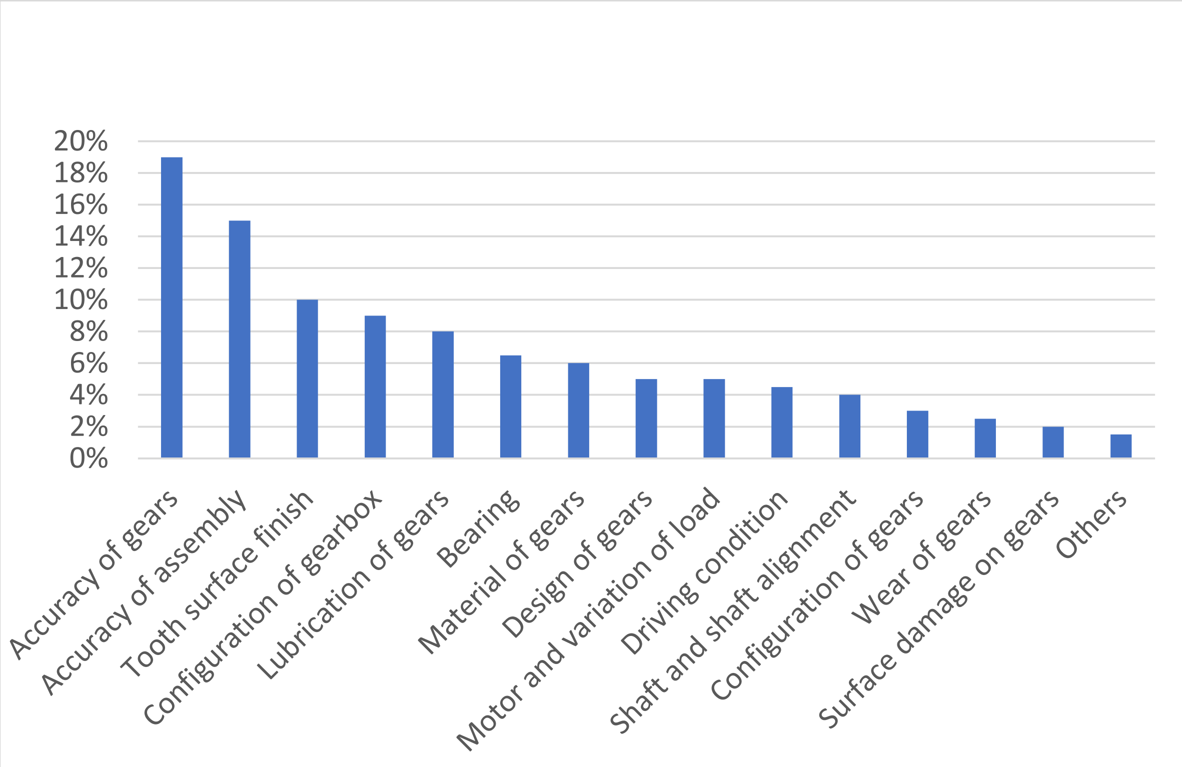


Fig.1.2: Different factors contributing to the generation of noise and vibrations in gears. (http://khkgears.net/gear-knowledge/introduction-to-gears/gear-noise/).

According to location of noise occurrence, gear noise can be divided broadly into two categories: (i) noise occurring from the gear itself, and (ii) noise from the peripheral components such as gearboxes.

When noise is from the gear itself, it can be due to friction between meshing gear teeth. Frequency of such noise is relatively low in most of the cases. It can be caused by many factors but most important factors are gear accuracy and transmission errors. These are considered to be an important excitation mechanism for gear noise. Accuracy of a gear is low due to errors in its microgeometry (such as profile error, pitch error, runout, flank surface topography) and teeth shape. This causes gear noise and vibration because teeth do not mesh as per theory. Even when accuracy of a gear is high and shape of its teeth is theoretically correct, the tooth bearing could be uneven when a gear shaft is warped due to pressure on a gear. In such situation, the gear noise can be reduced by (i) adjusting the gear bearing, (ii) improving the rigidity of gear shaft, and (iii) modifying gear tooth profile by crowning. Smooth meshing of gear teeth is an important factor to limit gear noise and vibration. Some measures to ensure smooth meshing gear teeth are:

(i) using profile-shifted gears to prevent interference, (ii) having a reasonable backlash, (iii) lubricating a gear, and (iv) smoothening gear tooth flank surfaces smooth by reducing their surface roughness.

Gearbox is often the cause of gear noise among peripheral components of a gear. In most of the cases, noise occurs when vibration from a gear are transmitted to the gearbox making it vibrate sympathetically and producing airborne noise. Frequency of such noise is generally higher than that of the noise due to friction between gear teeth. Noise caused by gearbox can reduced by (i) improving rigidity of a gearbox, (ii) using cast iron to manufacture gear, gearbox, and gear boss because cast iron has high vibration damping capacity, (iii) enhancing the front gear contact ratio by reducing the reduction ratio of a gear, (iv) improving the overlapping meshing ratio with a helical gear, and (v) using measures to reduce the gear noise because gearbox noise is caused by vibration the gear itself.

1.5 Measurement of Noise

Sound is a mechanical wave which create disturbance in pressure, density, displacement, and velocity of the medium of its propagation (known as acoustic medium). It travels as longitudinal wave in the fluids and as transverse and longitudinal waves in the solids. Noise is the unwanted sound. Most commonly measured attributes of sound are sound pressure 'p', sound intensity 'I', and sound power 'W'.

- **Sound pressure:** Sound pressure is measured by a microphone. Its SI unit is Pascal (Pa). It is difficult to plot variation of the sound pressure on linear scale due to its very wide measurement range therefore logarithmic scale in terms of decibel (i.e. one-tenth of a bel and denoted by dB) is used. Following different logarithmic relations are used to express different measures of sound pressure in dB. Figure 1.3 shows typical variation of total pressure [which is algebraic sum of atmospheric pressure and instantaneous sound pressure i.e. $p_{total}(t) = p_{atm} + p(t)$] with time.

Instantaneous sound pressure level $$L_{p(t)} = 20\, log_{10}\left(\frac{p(t)}{p_{ref}}\right) \text{dB} \quad (1.1)$$

Mean square sound pressure level $$L_{pms} = 10\, log_{10}\left(\frac{\overline{[p(t)]^2}}{p_{ref}^2}\right) \text{dB} \quad (1.2)$$

Root mean square sound pressure level $$L_{prms} = 20\, log_{10}\left(\frac{p_{rms}}{p_{ref}}\right) \text{dB} \quad (1.3)$$

Where, p_{atm} is the atmospheric pressure (Pa); *p(t)* is the instantaneous value of sound pressure at time '*t*' (Pa); p_{rms} is the root mean square of the sound pressure (Pa); p_{ref} is the reference value of the sound pressure in air which approximately corresponds to the threshold of normal hearing at 1kHz (= 20 μPa).

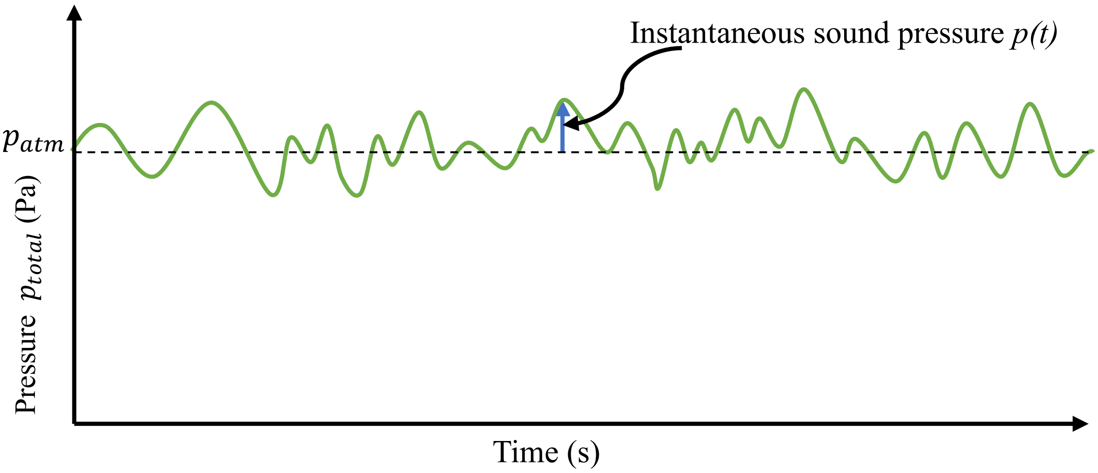


Fig. 1.3: Typical plot of varaition in the sound pressure with time **(Fhay, 2001).**

While measuring sound pressure level, distance of the measuring microphone from a sound source must be mentioned when there is only one source of sound i.e. for the measurements done at ambient or environmental conditions having some background noise then one meter distance from the sound source is a frequently used as the standard value. Because of the effects of reflected noise within a closed room, use of the anechoic chamber allows the measured sound to be comparable with sound measured in a free field environment.

- **Sound Intensity:** Sound intensity '*I*' is defined as the power of the sound wave per unit area. Sound intensity level 'L_I' is defined by the following equation

$$L_I = 10\, log_{10}\left(\frac{I}{I_{ref}}\right) \text{dB} \tag{1.4}$$

Where, I_{ref} is the reference sound intensity (W/m^2) that closely corresponds to sound intensity in the plane travelling wave whose mean square pressure equals to $p_{ref.}^2$ Its value is taken as 10^{-12} W/m^2.

- **Sound power:** Sound power 'W' is the power possessed by the sound wave. Sound power level 'L_w' is defined by following logarithmic equation in dB.

$$L_w = 10\, log_{10}\left(\frac{W}{W_{ref}}\right) \text{dB} \tag{1.5}$$

Where, W_{ref} is the reference sound power level that corresponds to the power passing through 1 m^2 of a plane wave having sound intensity equal to I_{ref}. Its value is taken as 10^{-12} W.

A-Weighted sound level: A-weighting is applied to the measured sound level to account for the relative loudness perceived by the human ear because human ear is less sensitive to low audio frequencies. A-weighting is an established, standard curve that attempts to alter the sound pressure levels recorded by a microphone to more closely match with perception of the human ear. It is employed by arithmetically adding a table of values, listed by octave or third-octave bands, to the measured sound pressure levels in dB. The resulting octave band measurements are usually added (logarithmic method) to provide a single A-weighted value describing the sound. A-weighted sound level is written as dB(A) or dBA.

1.6 Measurement of Vibrations

Vibration is to and fro motion of a particle or an object about its mean position. This motion may be periodic or aperiodic. Vibration can be measured in terms of displacement, velocity and acceleration. Generally, acceleration, velocity and displacement is measured for high frequency, intermediate frequency and low frequency vibrations respectively.

Every machine element has its own characteristics frequency at which it produces vibrations. In condition-based maintenance, vibration is a reliable tool for finding the health status of the machine elements by analysing their vibration signals. Each gear has its characteristic frequency which is known as gear mesh frequency (GMF). It is the rate at which gear teeth mesh together in a gearbox.

$$\text{GMF (Hz)} = \textit{Number of gear teeth (Z)} \times \textit{rotation per second of the gear (N)}$$

For measuring the vibrations of a gear, the accelerometer is mounted on the shaft bearing of the gear or gearbox as shown in Fig. 1.4. Accelerometer converts mechanical vibration to analog electrical signals which are converted to digital signals by an analog to digital converter. Vibration signal in time domain and frequency domain is shown in Figs. 1.5a and 1.5b respectively.

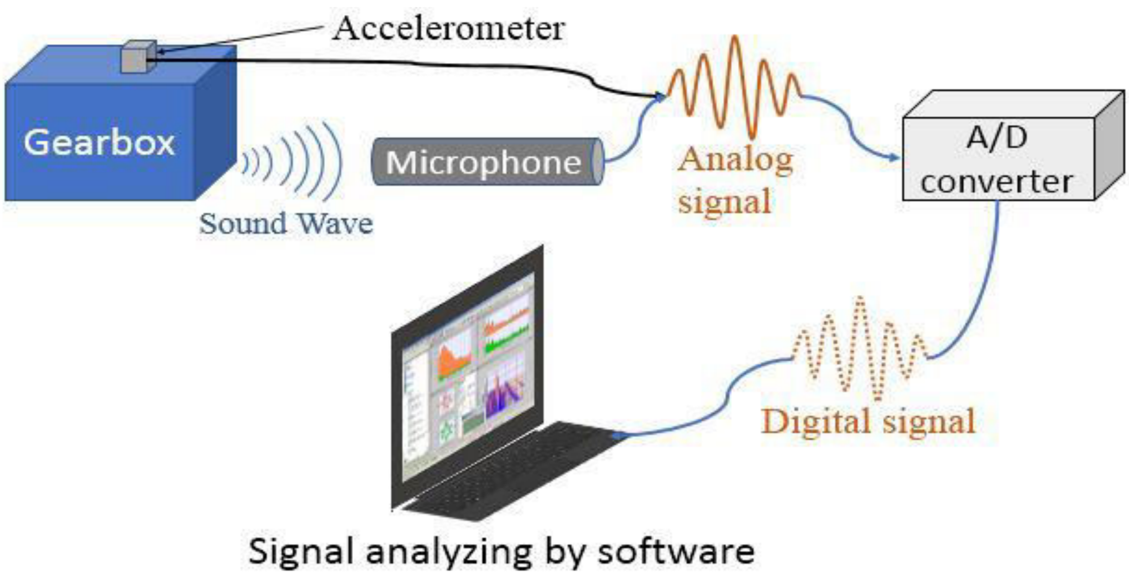
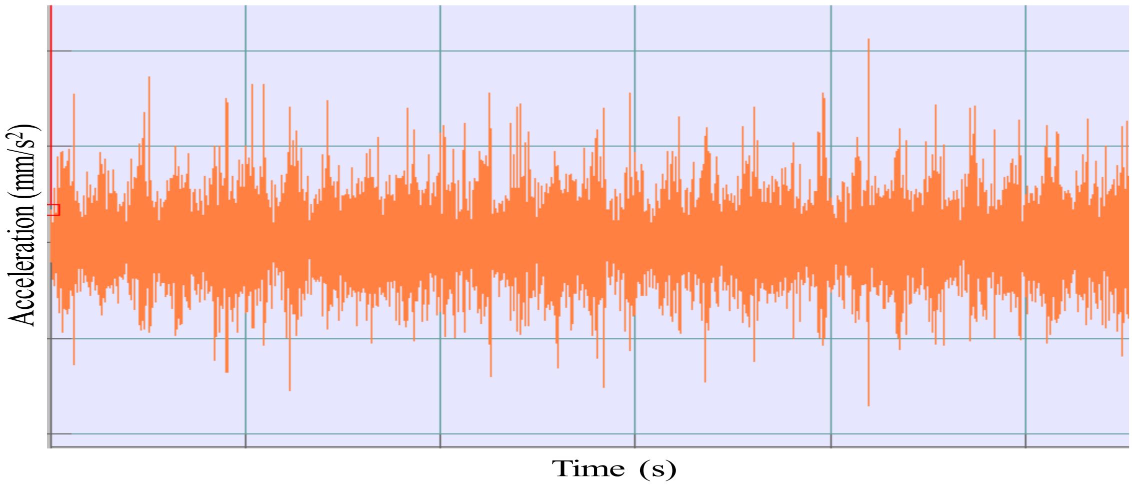
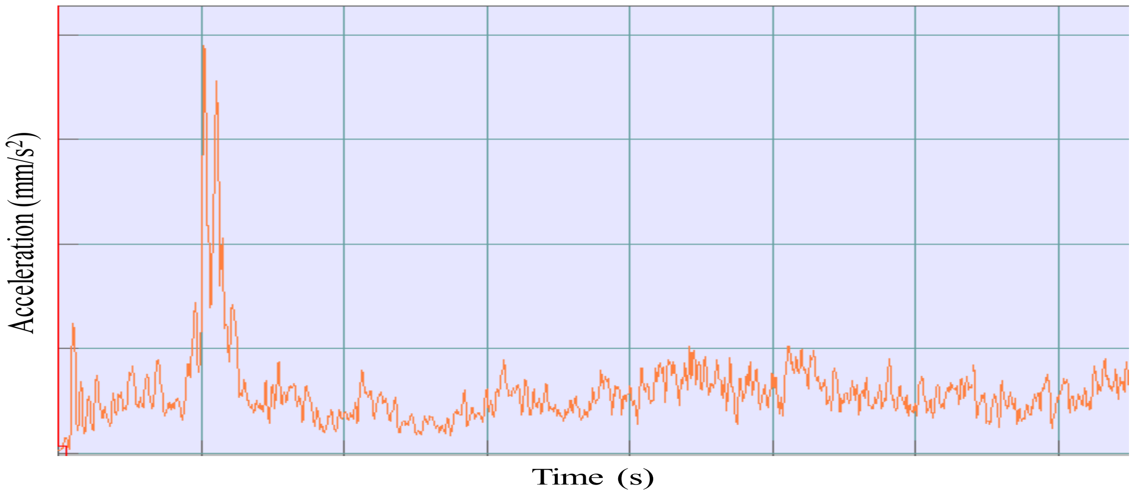


Fig 1.4: Measurement of noise and vibrations of a gearbox.



(a)



(b)

Fig. 1.5: Vibration signal in (a) time domain, and (b) frequency domain.

1.7 Reduction of Noise and Vibrations in Gears

Noise and vibration are generated in gears due to the several reasons. Their reduction depend upon following factors.

- **Gear Material**: High damping capacity material is lowering the vibration and hence noise. For reducing the noise and vibration gear material should be highly damped. Cast iron can be used as a highly damped material for manufacturing gears.
- **Using Resin Materials:** Plastic gears will be quiet in light load and low speed operation. Care should be taken to decrease backlash, caused from enlargement by absorption at elevated temperatures.
- **Module**: Using gears having smaller module and a larger number of gear teeth help in reducing the noise and vibration. Smaller the module smaller the teeth for a constant pitch circle diameter.
- **Using High-Rigidity Gears:** Increasing face width can give a higher rigidity that will help in reducing noise. Reinforce housing and shafts to increase rigidity.
- **Interference:** For avoiding the interference, chamfering the corner of the top land and modifying the tooth profile is done. It ensures smooth meshing of the gear teeth which results in lesser noise and vibration.
- **Ensuring Correct Tooth Contact:** Crowning and end relief can prevent edge contact. Proper tooth profile modification is also effective. Eliminate impact on tooth surface.
- **Proper Amount of Backlash:** A smaller backlash will help produce a pulsating transmission. A bigger backlash, in general, causes less problems.
- **Increasing Transverse Contact Ratio:** A bigger contact ratio lowers the noise. Decreasing the pressure angle and/or increasing the tooth depth can produce a larger contact ratio.
- **Increasing Overlap Ratio:** Enlarging the overlap ratio will reduce the noise. Because of this relationship, a helical gear is quieter than the spur gear and a spiral bevel gear is quieter than the straight bevel gear.
- **Avoiding too much thinning of the Web:** Lightened gears with a thin web thickness make high-frequency noises.
- **Finishing of Gears:** Finishing of gears reduces surface roughness as well as microgeometry parameters (total profile error, total lead error, total pitch error, radial runout). Lower the deviation in involute profile than ideal involute profile

ensure better engagement of teeth so less noise and vibration generated by finished gear pairs. Conventional finishing processes of gear include gear shaving, grinding, lapping, honing, burnishing, skiving or running in gears in oil for a period of time. Advanced finishing processes include electrochemical honing (ECH), abrasive flow finishing (AFF), water jet finishing (WJF) and abrasive water jet finishing (AWJF).

- **Lubrication:** Sufficient lubrication of gears ensuring hydrodynamic lubrication between the meshing gears reduces gear noise. Use of high viscosity lubrication also reduces gear noise. If lubricant is trapped in the roots of the meshing teeth and cannot escape fast through backlash gap, it will be expelled forcibly axial can impact on the end walls of the gearcase.
- **Lower Load and Speed:** Lowering rotational speed and load as far as possible will reduce gear noise.
- **Using Gears without Dents:** Gears which have dents on the tooth surface or the tip make cyclic, abnormal sounds.

1.8 Different Finishing Processes for Gears

Following are the conventional finishing processes used for the gears **(Petare and Jain 2016)**

1.8.1 Conventional Finishing Processes

1.8.1.1 Gear Grinding: Gear grinding is used to correct the thermal distortions after heat treatment of gears and to improve the surface finish and microgeometry. It can finish hardened gear having hardness more than 40 HRC. Transverse grind lines on tooth surface cause noise and vibration.

1.8.1.2 Gear Lapping: It improves wear properties. It is costly and very slow process. It gives very minute improvement in profile error and lead error.

1.8.1.3 Gear Honing: It improves functional characteristics, geometric accuracy, roughness, dimensional accuracy, lay pattern and integrity of the gears. It is an economical process for gear finishing. Crowning can also be done by this process.

1.8.1.4 Gear Shaving: Gear shaving removes a small amount of material from the workpiece gear to correct errors in its profile, pitch, helix angle, eccentricity, and improves the surface finish of the gear. It provides profile modifications that improve load carrying capacity of gear. This process can finish gears having hardness value up to 40 HRC only. A step mark left on gear teeth at the end of the involute profile which causes noise and vibration. It removes more material from the pitch surface deteriorating transmission efficiency of the shaved gears.

1.8.1.5 Gear Burnishing: Burnishing can finish only unhardened gears. It cannot improve tooth position, tooth profile, lead, spacing, or concentricity.

1.8.6 Advanced Finishing Processes

1.8.6.1 AFF (Abrasive Flow Finishing): AFF does not give any undesirable effects during gear finishing unlike given by the conventional finishing process i.e. (i) grinding burns in gear grinding, (ii) microgeometry errors due to longer lapping cycles in gear lapping, and (iii) removal of more material from the pitch surface deteriorating transmission efficiency in gear shaving. The gear flank surfaces finished by AFF process is free from mechanical, thermal stresses, and related distortions due to the controlled predefined movement of the abrasive particles and AFF medium working as a coolant absorbing the heat generated while abrading the flank surface of gear.

1.8.6.2 Electrochemical Honing (ECH): This process can finish gears of any hardness irrespective of heat treatment. It corrects an error in helical angle, tooth profile and eccentricity.

1.9 Organization of Thesis

Chapter 2 present review of the past work on the effect of finishing on gear noise and vibrations, the identified research gaps, the research objectives of the present work to bridge the identified research gaps, and the research methodology used to meet the research objectives of the present work.

Chapter 3 presents a detailed explanation of the experimental apparatus and instruments used for noise and vibrations as well as for finishing.

Chapter 4 presents results of noise and vibrations of helical gears and surface finish and microgeometry.

Chapter 5 about conclusions of the present work and scope for the future work.

Chapter 2

Review of the Past Work

This chapter describes review of the past work on gear noise and vibrations and on finishing of gears by different advanced finishing processes, the identified research gaps, and the research objectives defined to bridge the identified research gaps, and research methodology used in the present work.

2.1 Past Work on Gear Finishing Effect on their Noise and Vibrations

Liu et *al.* (1990) conducted 242 experiments on spur gears used in headstocks of the machine tools in which they compared the noise of the spur gears ground on different gear grinders. They reported that gears with better surface finish had lower noise than the unfinished gears. They reported 85 dB and 75.7 dB as maximum and minimum values of noise level respectively. They also observed that gears having a smaller value of pitch error, profile error and transmission error reduced the average noise level by 4 dB. They concluded that gear finishing is the key technology in ensuring better accuracy of the gears. They also reported that gear noise decreased by 5-6 dB by internal honing.

Akerblom and Pärssinen (2002) performed experimentation on eleven different test gear pairs finished by gear shaving and gear grinding. The shaved gears were less noisy than the ground gears. They reported that transmission error is an important excitation mechanism for gear noise. Following are the conclusion made by their research

- Shaved gears do not seem to be noisier than ground gears, even if they show considerable gear tooth deviations.
- Gears ground with the threaded grinding wheel are less noisy than the profile ground gears.
- Rougher surface increases gear noise in range of 1 to 2 dB especially at low torque level.
- Wider gears, with overlap ratio =1.8, decrease both noise and vibration by approximately 5 dB.
- Increased lead crowning increases noise and vibration levels by 1dB.
- Decreased lead crowning decreases noise and vibration levels by between 1 and 3dB.
- Helix angle error (37μm) increases noise level by 1 to 3 dB.

Jolivet et *al.* (2015) compared vibrations of the gears finished by grinding and power honing. They reported that ground gears produce lesser vibrations than the power honed gears and difference being 0.2 dB at first harmonic and 0.3 dB at second and third harmonic. They used multiscale analysis based on continuous wavelet transform to study the teeth topography as well as the vibrations.

Jolivet et *al.* (2016) studied the simultaneous effect of tooth roughness and lubricant viscosity on gearbox vibrations. Higher surface roughness led to increase of noise induced by friction during the contact that occurs between surface asperities. Surface roughness had a large impact on gear vibrations in dry and wet conditions.

2.2 Past work on Finishing of Gears by AFF

Xu et *al.* (2013) investigated the effect of AFF on the surface of the helical gear. They used CFD module of the COMSOL multiphysics software to find the distribution of the velocities, shear rates and shear forces of the abrasive flow. The average surface roughness of left tooth surface, right tooth surface and addendum were used for comparison and found the surface quality of helical gear improved effectively after finishing by AFF.

Venkatesh et *al.* (2014) investigated the effect of few critical parameters of AFF such as extrusion pressure, abrasive mesh size, processing time and media flow rate on the finishing of straight bevel gears made of EN-8 steel. They reported that AFF improved surface finish by more than 50% , the extrusion pressure has the highest contribution of about 73% on the process output followed by abrasive mesh size and processing time, media flow rate does not affect finishing process, and the tooth surface morphology improves with an increase in extrusion pressure.

Petare and Jain (2018a) presented comprehensive and detailed explanation on process modeling, rheological characterization of the AFF medium, development of finishing medium, development of various hybrid, derived, and hybrid-derived processes of AFF, and some novel applications of AFF for complicated shapes and difficult-to-finish materials. They concluded design of the fixture varies according to geometry and size of the component to be finished and design of the machine and workpiece fixture for AFF process and selection of finishing medium are major challenges and the most important aspects affecting its performance.

Petare and Jain (2018b) investigated the influence of media viscosity and finishing time on error reduction in total profile, total lead, total pitch, runout and average surface roughness of spur gears. Twenty experiments were conducted varying AFF medium viscosity at four levels and finishing time at five levels. Maximum percentage reduction in total profile error, total lead error, total pitch error were obtained at 135 kPa.s viscosity of AFF medium and 25 min of finishing time, and maximum percentage reduction in runout error was obtained at 54 kPa.s viscosity and 20 min finishing time.

2.3 Identified Research Gaps

Following research gaps were identified based on the review of the relevant past work reported in the literature on noise and vibrations of helical gears.

- Limited research has been reported on the microgeometry and surface finish improvement of the helical gears by their finishing.
- No work has been reported on studying effects of the advanced finishing processes on noise and vibrations of the helical gear.
- No work has been reported to minimise the microgeometry errors of the helical gear by AFF process.

2.4 Objectives of the Present Research Work

- Comparison and analysis of noise and vibration levels of helical gear pair finished by AFF process with unfinished (i.e. hobbed) helical gear pair.
- Find the relationship between noise and vibrations with micro-geometry and surface quality of helical gears.
- Finding the most critical parameter of micro-geometry and surface quality which affects noise and vibration of helical gears.

2.5 Research Methodology

Fig. 2.1 presents research methodology used in the present work.

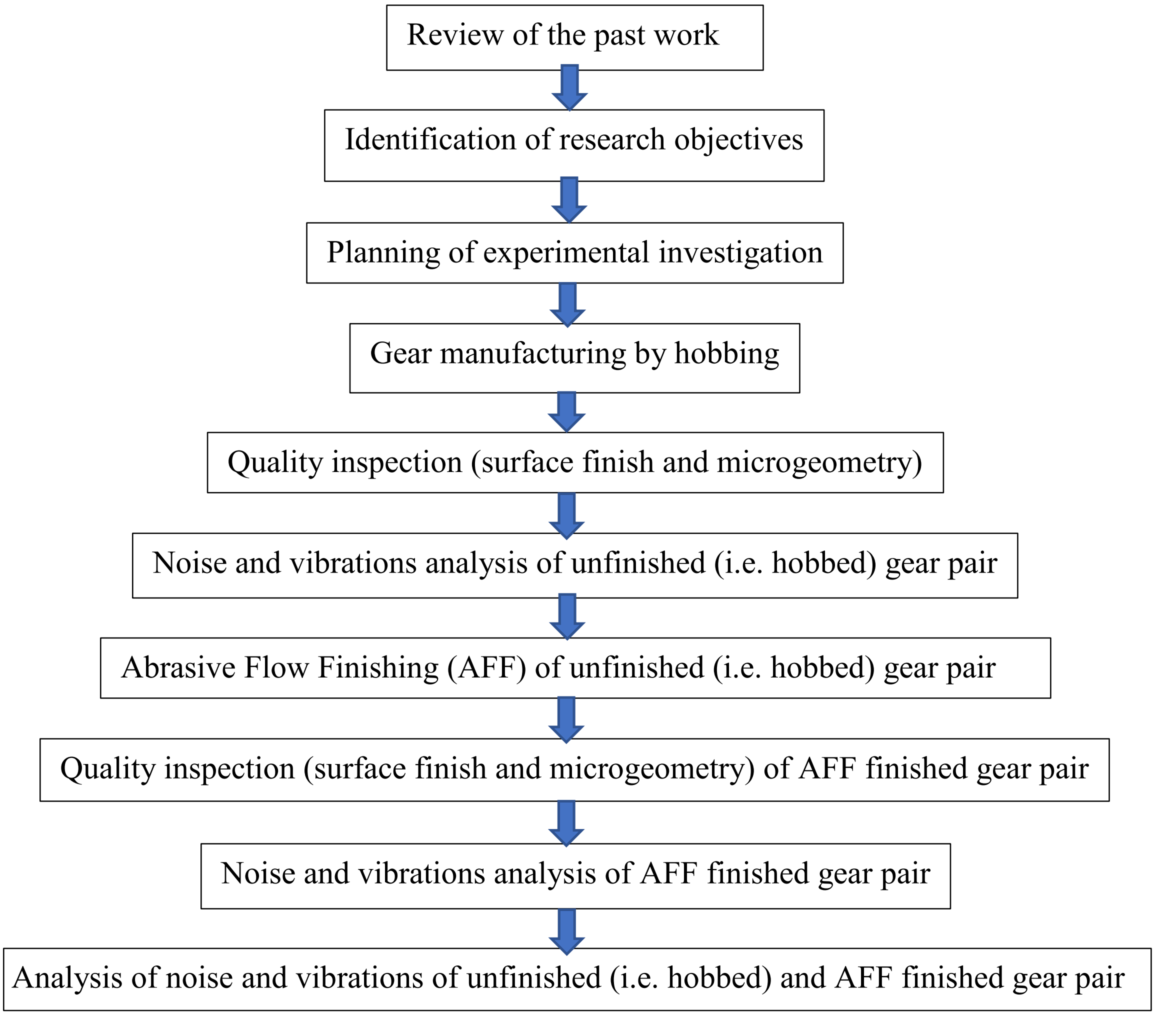


Fig. 2.1: Reseach methodology used in the present work.

Chapter 3

Details of Experimentation

This chapter presents details of helical gear manufacturing, their quality inspection, their finishing by abrasive flow finishing process, and measurement of noise and vibrations of the unfinished and AFF finished helical gear pair.

3.1 Manufacturing of Helical Gears

Pinion and gear having specifications as mentioned in Table 3.1 were manufactured on gear hobbing machine using the sequence shown in Fig. 3.1.

Table 3.1: Specifications of pinion and gear.

Parameter	**Pinion**	**Gear**
Material	20MnCr5 alloy steel	20MnCr5 alloy steel
Module	3 mm	3 mm
Pressure angle (ϕ)	20^o	20^o
Helix angle (ψ)	16^o Left Hand	16^o Right Hand
Number of Teeth	21	36
Pitch circle diameter	65.54 mm	112.35 mm
Addendum Circle diameter	71.54 mm	118.35 mm
Root Circle Diameter	58.04 mm	104.85 mm

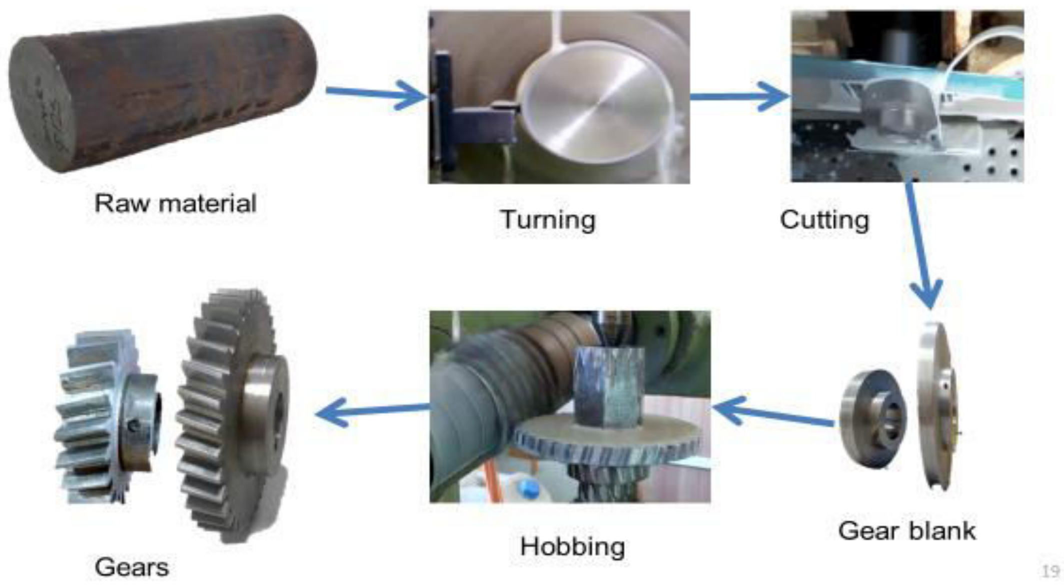


Fig. 3.1: Manufacturing of helical gears by hobbing.

3.2 Finishing of Helical Gears by Abrasive Flow Finishing (AFF)

AFF is an advanced Finishing process. This process uses viscoelastic self-deformable putty which consists of abrasive particles acting as individual cutting tools. Two vertically opposed cylinders extrude abrasive media back and forth through passages formed by fixture and workpiece.

AFF experimental apparatus, as shown in Fig. 3.2, developed by Petare and Jain (2018b) was used to finish the helical gear pair. It has two medium containing cylinders, two hydraulic cylinders, workpiece fixture space, pressure control valve and hydraulic power unit. AFF putty flows from one medium containing cylinder to another cylinder by the piston of hydraulic cylinder which is controlled by the hydraulic power unit.

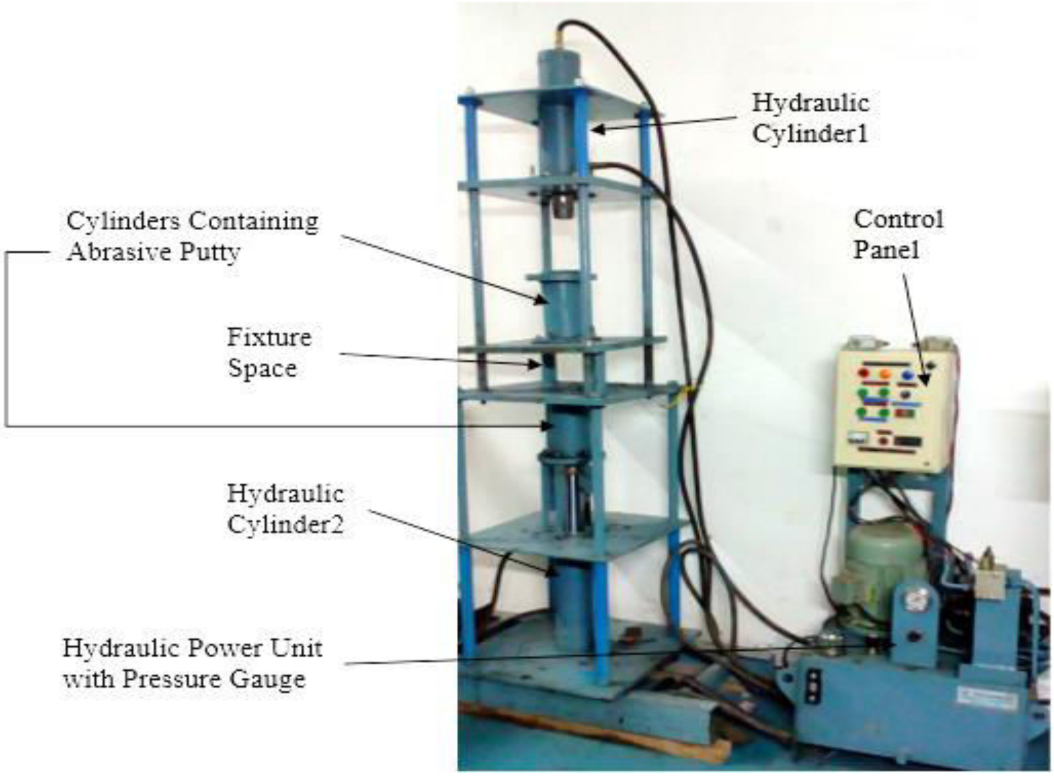
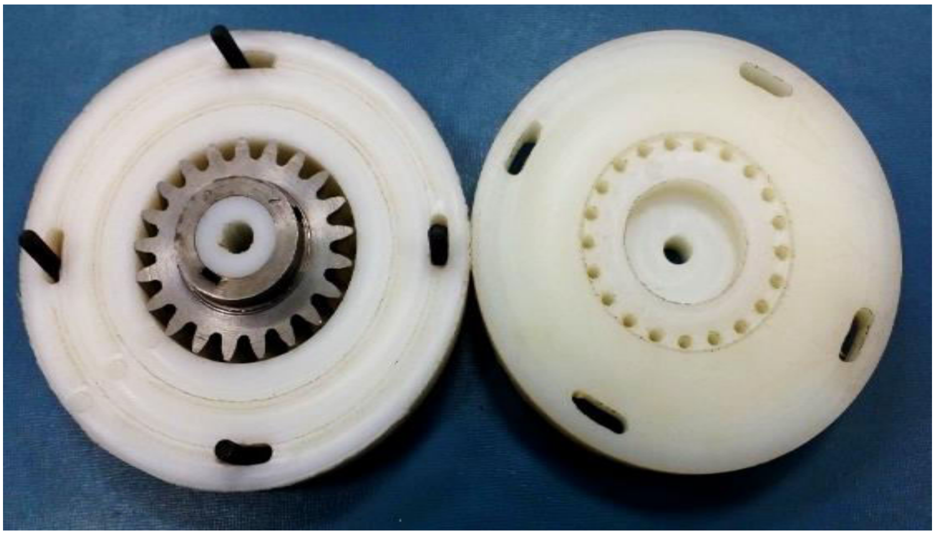


Fig. 3.2: AFF apparatus developed by **Petare and Jain (2018b).**

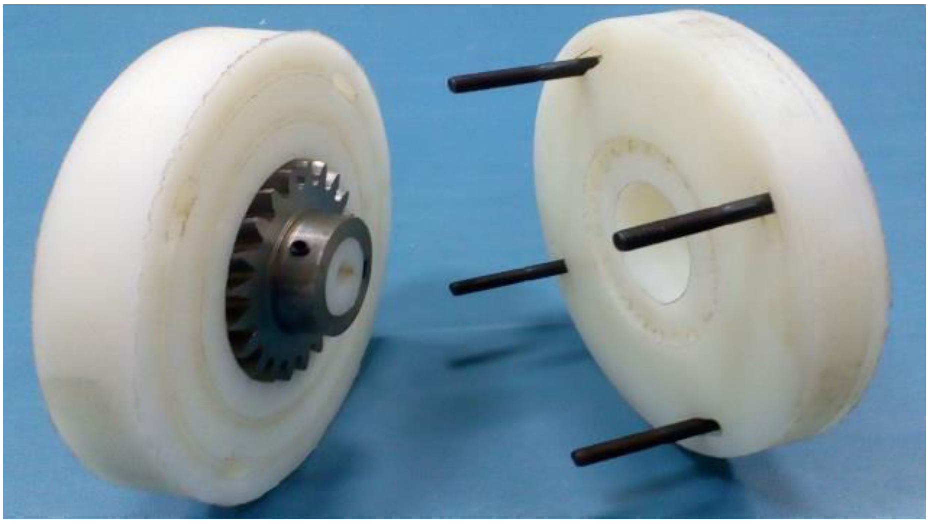
3.2.1 Design of Fixtures for AFF of the Helical Gears

Fixture help in holding the workpiece gear between medium containing cylinders. Fixtures were designed and developed for both pinion and gear. AFF fixture for pinion has two parts having a circumferential equispaced hole of diameter 6.5 mm at the pitch circle diameter equal to the number of teeth. AFF medium containing cylinders have a diameter of 103 mm and workpiece gear has an outer diameter of 118.35 mm therefore, gear cannot be held between fixture having only two half parts unlike for pinion.

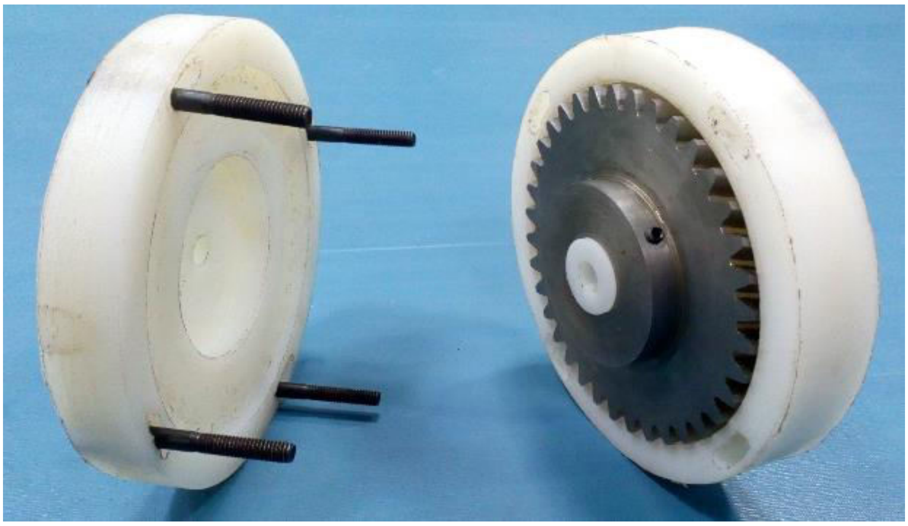
Therefore, for gear there were two additional parts that were designed and developed as shown in Fig. 3.3d. The material for AFF Fixture was chosen to be metalon due to its high compressive strength and non-reactive nature with AFF medium.



(a)



(b)



(c)

(d)

Fig. 3.3: Fixture designed and developed for (a) and (b) for pinion, (c) and (d) for gear.

3.2.2 Parameters Used in Helical Gears Finishing by AFF

The optimum values of AFF parameter for spur gears identified by **Petare and Jain (2018b)** were used for finishing of the helical gear by AFF process. They are mentioned in Table 3.2.

Table 3.2: Parameters used to finish helical gears by AFF

Parameter	**Optimum value**
Abrasive type	SiC (Silicon Carbide)
Abrasive particle mesh size	100
Volumetric concentration of abrasive particle	30%
Volumetric concentration of silicon oil	10%
Extrusion Pressure	5 MPa
Finishing Time	25 minute

3.2.3 Procedure of Finishing Helical Gears by AFF

Helical gears were finishing by AFF process using the following procedure:

- ❖ AFF Medium of the required composition and concentration was prepared by manual mixing and keeping in view all the required considerations.
- ❖ The prepared AFF medium was filled in the medium-containing cylinders.
- ❖ The workpiece gear or pinion was fixed in the corresponding fixture ensuring that there is no rotation of gear or pinion in the fixture and axis of the gear or pinion is parallel to the axis of the central hole provided in the corresponding fixture.

- Gear or pinion containg fixture were placed between medium containing cylinder sand clamped with bolts ensuring that there is no leakage of the AFF medium during the gear finishing.
- The pressure exerted by hydraulic cylinders maintained reciprocation speed of the AFF medium and limit switch set the stroke length.
- Extrusion pressure control was by a hydraulic pump.
- Finishing timing was measured using a stopwatch.
- After each experiment, the workpiece gear was washed with tap water and cleaned with cotton and dipped in the oil to avoid its rusting due to exposure to putty in the finishing fixture.

3.3 Measurement of Surface Roughness of Helical Gears

Three parameters of surface roughness namely average surface roughness 'R_a', maximum roughness 'R_{max}' and mean roughness depth 'R_z' were measured on Marsurf LD130 from ***Mahr Metrology, Germany***. Percentage improvement in average surface roughness PIR_a was computed by the following equation 3.1

$$PIR_a = \frac{R_a\ value\ before\ finishing\ -\ R_a\ value\ after\ finishing}{R_a value\ before\ finishing}\ 100 \qquad (3.1)$$

Similarly, percentage improvement computed for maximum roughness depth (R_{max}) and mean roughness depth (R_z).

3.4 Inspection of Microgeometry of Helical Gears

Under microgeometry form error (total profile error 'F_a', total lead error 'F_b') and location error (cumulative Pitch error 'F_p', total runout 'F_r') were inspected on gear metrology machine ***Smart-gear*** from ***WenZel Gear Tec***, ***Germany***. Deutsche Normen (DIN) and American Gear Manufacturers Association (AGMA) are the universally accepted standards for denoting the quality of gears regarding microgeometry error. Higher AGMA number or lower DIN number shows better quality of the gears. Following equations were used for computing average value of percentage improvement in total profile error (PIF_a).

$$Avg.PIF_a = \frac{Avg.\ F_a\ value\ of\ unfinished\ gear\ -Avg.F_a\ Value\ of\ finished\ gear}{Avg.F_a\ \ value\ of\ unfinished\ gear}\ 100 \qquad (3.2)$$

Similarly, average value of percentage improvement for total lead error 'F_b', cumulative pitch error 'F_p' computed. Percentage improvement in radial runout 'F_r' computed by following equation because radial runout yields single value.

$$PIF_r = \frac{F_r\ value\ for\ unfinished\ gear - F_r\ value\ for\ finished\ gear}{F_r\ value\ of\ unfinished\ gear} 100 \quad (3.3)$$

3.5 Measurement of Noise and Vibrations

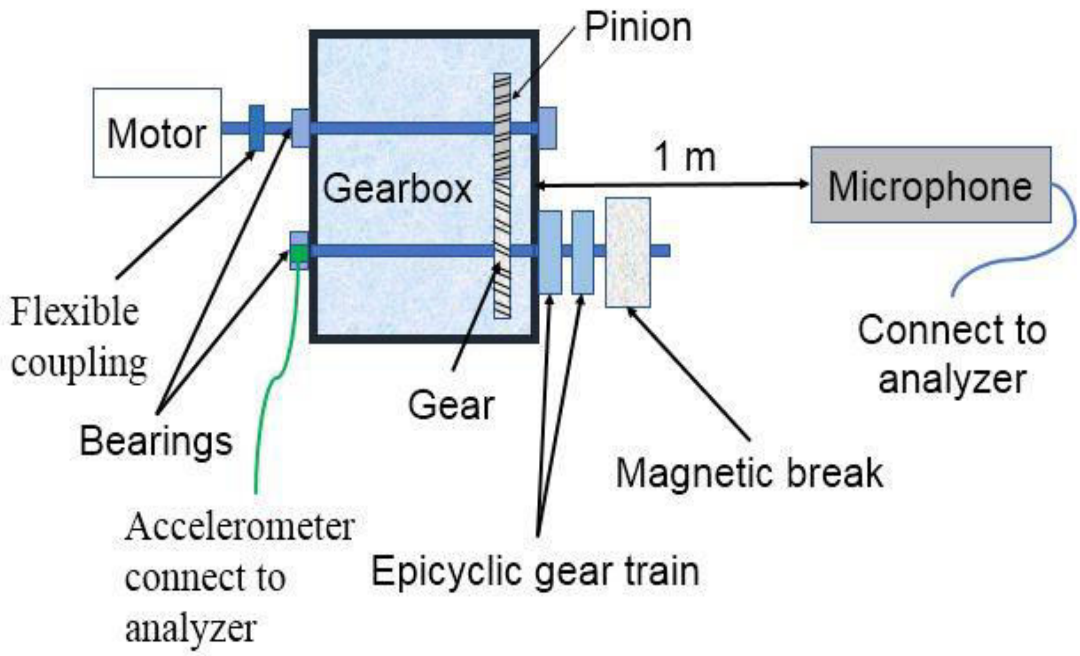
Figure 3.4a shows schematic diagram and Fig. 3.4b depicts photograph of the arrangement of equipment used for measurement of noise and vibration of pair of helical gear and pinion. In this, pair of AFF finished gear and pinion and unfinished gear and pinion was mounted in the **drivetrain diagnostics simulator** (DDS) which consists of two-stage parallel shaft gearbox, two-stage planetary gearbox and a programmable magnetic break. It is designed to investigate gearbox dynamics and sound behaviour, health monitoring, vibration-based diagnostic techniques, lubricant conditioning and wear particle analysis. Accelerometers can be mounted on the gearbox or on the bearing housing to measure the vibrations in all three directions. Magnetic break applies a torsional load on gear in the range of 2.034 Nm to 43.386 Nm. It has maximum speed of 2850 rpm.

OROS OR35 **data acquisition system** (Fig. 3.5) was used for collecting signals of noise and vibration of the gear pair. It has four input, two output and two synchronous input channels. It is 24bit size data acquisition system having input range as ±10 volts. NV Gate 9.0 software was used for analyzing the acquired noise and vibration signals.

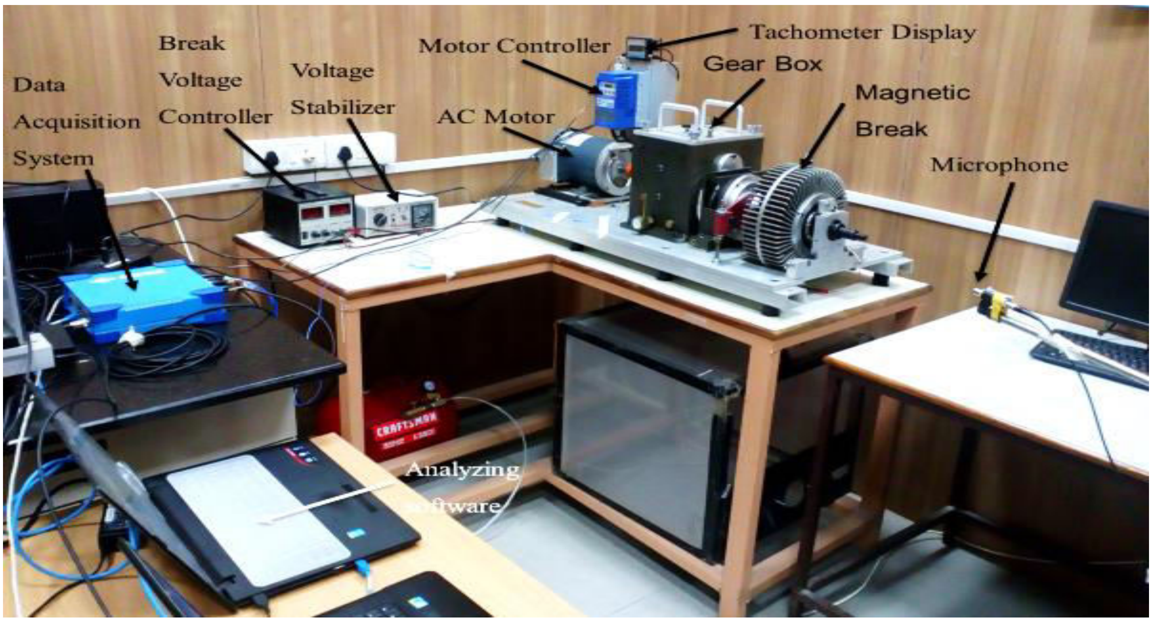
Triaxial **accelerometer** (Model: 356A16 PCB and shown in Fig. 3.6a) having sensitivity 10.52; 10.57; and 10.51 mV/m/s^2 along X, Y, and Z-axis respectively was used to measure gearbox vibrations. It has Integrated Circuit Piezoelectric (ICP) and sensors which have built-in microelectronics which convert a high-impedance charge signal generated by a piezoelectric sensing element into a usable low-impedance voltage signal that can be readily transmitted to any data acquisition system through the cable (shown in Fig. 3.6b). The triaxial accelerometer was mounted on bearing housing (Fig. 3.7a) such that axial direction is Y-axis, the tangential direction is Z-axis, and the radial direction is X-axis.

Microphone is a transducer which converts pressure energy (sound wave) to electrical energy. Condenser type microphone consists of a thin electrically conductive membrane close to a solid metal plate. When the sound wave hit the microphone then the thin membrane (diaphragm) deflects backwards and forwards and hence change in voltage is observed. Condenser type microphone (Capacitor Microphone) from ***Microtech Gefell*** (depicted in Fig.3.8) and having a sensitivity of 42.9 mv/Pa was used to collect the noise signals in the present work.

Speed of the motor of DDS was controlled manually by VFD (Variable Frequency Drive). Vibration and noise signals were recorded at five loading conditions namely no-load (0%), 15%; 30%; 45%; and 60% of full load (i.e. 43.386 Nm) for four speed (i.e. 400; 800; 1,200; and 1,600 rpm).



(a)



(b)

Fig. 3.4: Arrangement of equipment used for measurement of noise and vibrations of pair of unfinished and AFF finished pair of helical gear and pinion: (a) schematic diagram, and (b) photograph.

(a)

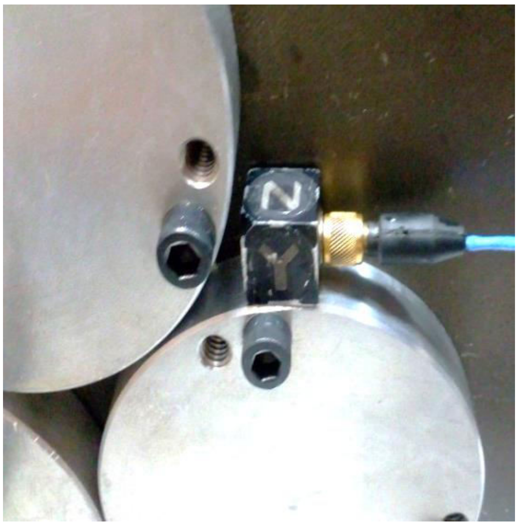
(b)

Fig. 3.5: Data acquisition system for noise and vibration signals: (a) front panel, and (b) pack panel.

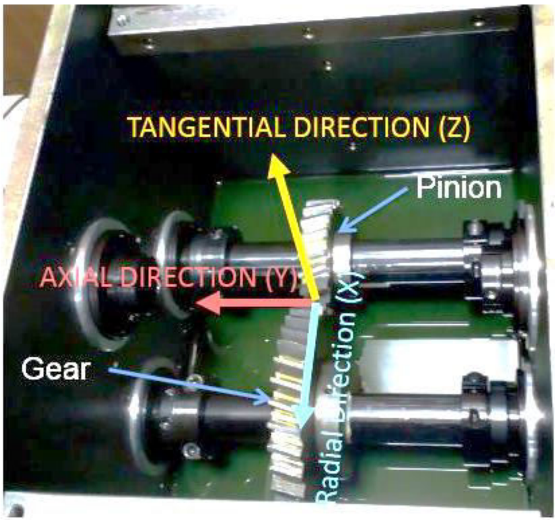
(a)

(b)

Fig. 3.6: (a) Triaxial accelerometer, and (b) cable used for connecting the accelerometer to the data acquisition system.



(a)



(b)

Fig. 3.7: (a) Mounting of the triaxial accelerometer on bearing housing, (b) tangential, axial and radial directions inside the gearbox.

Fig. 3.8: Condenser type microphone used to collect noise signals.

Chapter 4

Results and Discussion

This chapter describes results of measurements of the surface finish, microgeometry errors, noise and vibrations of an unfinished (i.e. hobbed) gear pair and a finished gear pair.

4.1 Results for Surface Roughness

Three parameters of surface roughness i.e. average surface roughness 'R_a', maximum roughness 'R_{max}' and mean roughness depth 'R_z' were measured of unfinished (i.e. hobbed gears) and after AFF finishing of helical gear and pinion is shown in Table 4.1. percentage improvement in surface roughness parameters is calculated using Eq. 3.1.

Table 4.1: Surface roughness values for unfinished (i.e. hobbed) and AFF finished gear pair.

		Pinion	Gear
Average surface roughness R_a (μm)	Before finishing	0.77	1.99
	After finishing	0.48	1.62
	PIR_a (%)	37.80	18.5
Maximum roughness R_{max} (μm)	Before finishing	6.58	14.01
	After finishing	5.68	10.67
	PIR_{max} (%)	13.70	23.90
Mean roughness depth R_z (μm)	Before finishing	5.07	10.23
	After finishing	3.44	7.75
	PIR_z (%)	32.20	24.30

4.2 Results for Microgeometry Errors

Total profile error 'F_a', total lead error 'F_b', total pitch error 'F_p' and radial runout 'F_r' were measured for unfinished (i.e hobbed gears) and after AFF finished helical gear and pinion is shown in Table 4.2. After AFF finishing microgeometry errors are reduced except total lead error for pinion increased by 3.04%. Average percentage improvement for microgeometry errors (total profile error 'F_a', total lead error 'F_b', total pitch error 'F_p') is calculated using Eq. 3.2 and for radial runout uing Eq. 3.3. Percentage improvement in microgeometry errors is more for pinion than gears because of different design of AFF fixture used for pinion and gear.

Table 4.2: Microgeometry errors for unfinished (i.e. hobbed) and AFF finished gear pair.

		Value for pinion (DIN quality)	Value for gear (DIN quality)
Total Profile Error F_a (μm)	Avg. F_a before finishing (μm)	658.2 (DIN12)	266.85 (DIN 12)
	Avg. F_a after AFF (μm)	384.55 (DIN 12)	244.1 (DIN 12)
	Avg. PIF_a (%)	41.57	8.5
Total Lead Error F_b (μm)	Avg. F_b before Finishing (μm)	93.85 (DIN 12)	86.9 (DIN 12)
	Avg. F_b after AFF (μm)	96.7 (DIN 12)	70.5 (DIN 12)
	Avg. PIF_b (%)	-3.04	18.87
Total Pitch Error F_p (μm)	Avg. F_p before finishing (μm)	833.75 (DIN 12)	647.95 (DIN 12)
	Avg. F_p after AFF (μm)	454.95 (DIN 12)	496.75 (DIN 12)
	Avg. PIF_p (%)	45.43	15.12
Radial Runout F_r (μm)	F_r before finishing (μm)	1120 (DIN 12)	982.4 (DIN 12)
	F_r after AFF (μm)	656.9 (DIN 12)	872.6 (DIN 12)
	PIF_r (%)	41.34	11.17

4.3 Results for Vibrations Measurement

The vibration was measured at different speeds and loads as shown in Table 4.3 to 4.6 for both unfinished (i.e. hobbed) gear pair and AFF finished gear pair. The RMS value of vibration at GMF was obtained after transforming time domain signal into frequency domain signal as shown in Fig. 4.1 for 1600rpm and no load condition, similarly RMS value of vibration at GMF was obtained for other speed and load conditions. Comparisons of vibration of different speed and load conditions are shown in Fig. 4.2 to 4.9. Resultant acceleration is calculated using the following equation:

$$\text{Resultant acceleration } a_r = \sqrt{a_x^2 + a_y^2 + a_z^2} \qquad (4.1)$$

a_x = acceleration in radial direction (x-axis)

a_y = acceleration in axial direction (y-axis)

a_z = acceleration in tangential direction (z-axis)

Following are the conclusions made from comparisons of vibration levels:

- Vibration levels were increased with increase in load at all speeds.

- Vibration levels were maximum in tangential direction (Z-axis) and minimum in radial direction (X-axis) at GMF, while overall vibration levels were maximum in axial direction (Y-axis) and minimum in tangential direction (Z-axis) for unfinished gear pair for all load condition at each speed.
- RMS values of vibration levels were decreased at GMF for finished gear pair.
- At 400 rpm overall vibration levels were increased for finished gear pair but decrease at other speeds.

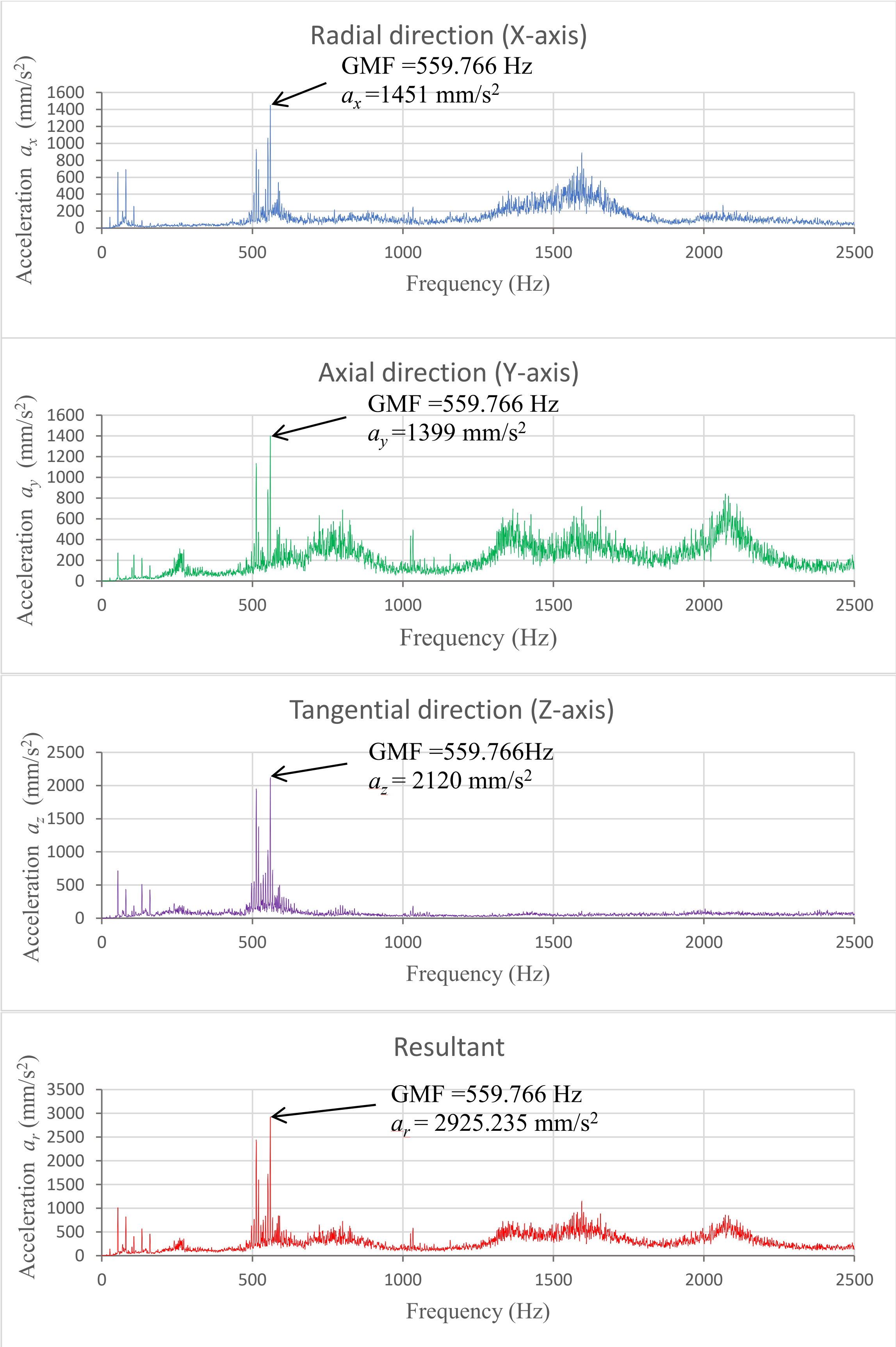


Fig. 4.1: Vibrations signals in frequency domain at 1600 rpm and no-load condition.

4.4 Vibrations Values of Hobbed Gear pair and Finished Gear Pair

Table 4.3: Vibrations values for the unfinished (i.e. hobbed) and AFF finished gear pair at 400 rpm.

Type of RMS value	Acceleration measurement direction	Percentage load (%)					Percentage load (%)				
		No load	15%	30%	45%	60%	No load	15%	30%	45%	60%
		Values for the unfinished gear pair (mm/s^2)					Values for the AFF finished gear pair (mm/s^2)				
RMS value of vibrations at GMF	Acceleration along radial direction (i.e. X-axis)	64.9	67.2	94.5	105.3	102.9	22.52	26.76	56.2	37.94	30.5
	Acceleration along axial direction (Y-axis)	82.5	95.8	117.2	153.2	146.4	68.8	115.8	99.7	92.9	92.6
	Acceleration along tangential direction (i.e. Z-axis)	279.8	238	216.3	250.5	263.2	241.4	187.3	160.1	177.6	166.3
	Resultant acceleration	298.84	295.21	263.54	311.94	318.27	252.02	221.83	196.8	203.99	192.77
RMS value of overall vibrations	Acceleration along radial direction (i.e. X-axis)	1071	1039	1095	1121	1112	941	982	1033	1069	1075
	Acceleration along axial direction (Y-axis)	1758	1730	1827	1915	1880	2060	2201	2292	2283	2190
	Acceleration along tangential direction (i.e. Z-axis)	971	956	1008	1045	1068	991	1034	1074	1112	1067
	Resultant acceleration	2276.06	2233.02	2356.48	2452.73	2431.37	2472.08	2622.57	2733.83	2755.25	2662.75

Table 4.4: Vibrations values for the unfinished (i.e. hobbed) and AFF finished gear pair at 800 rpm.

Type of RMS value	Acceleration measurement direction	Percentage load (%)					Percentage load (%)				
		No load	15%	30%	45%	60%	No load	15%	30%	45%	60%
		Values for the unfinished gear pair (mm/s^2)					Values for the AFF finished gear pair (mm/s^2)				
RMS value of vibrations at GMF	Acceleration along radial direction (i.e. X-axis)	90.5	114.1	168.6	248.1	293.7	73	77	92.9	87.9	78.3
	Acceleration along axial direction (Y-axis)	238.6	196.7	179.7	240.8	211.7	169.2	155.5	234.7	304.1	309.6
	Acceleration along tangential direction (i.e. Z-axis)	464	461.4	580	693	685	247.2	307.2	341.4	411.1	423.1
	Resultant acceleration	529.54	514.39	630.17	774.46	774.79	308.33	352.82	424.58	518.85	530.09
RMS value of overall vibrations	Acceleration along radial direction (i.e. X-axis)	3932	4049	4469	5030	5360	2285	2532	3331	3778	4248
	Acceleration along axial direction (Y-axis)	6450	6860	7680	8810	9390	5310	6040	7330	8400	9230
	Acceleration along tangential direction (i.e. Z-axis)	2586	2719	3009	3412	3577	2117	2347	2818	3069	3379
	Resultant acceleration	7984.39	8417.06	9381.28	10703.21	11388.44	6156.22	6957.08	8530.27	9708.34	10707.75

Table 4.5: Vibrations values for the unfinished (i.e. hobbed) and AFF finished gear pair at 1200 rpm.

Type of RMS value	Acceleration measurement direction	Percentage load (%)					Percentage load (%)				
		No load	15%	30%	45%	60%	No load	15%	30%	45%	60%
		Values for the unfinished gear pair (mm/s^2)					Values for the AFF finished gear pair (mm/s^2)				
RMS value of vibrations at GMF	Acceleration along radial direction (i.e. X-axis)	257.7	271.3	252.8	248	317.5	157.9	155.6	202.4	211.5	311.1
	Acceleration along axial direction (Y-axis)	220.2	305.3	434.5	679	696	183.4	196.1	387.5	486	739
	Acceleration along tangential direction (i.e. Z-axis)	555	585	713	946	982	160	142.6	261.2	231.3	264.5
	Resultant acceleration	650.32	713.47	872.39	1190.57	1244.81	290.12	288.10	509.26	578.30	844.31
RMS value of overall vibrations	Acceleration along radial direction (i.e. X-axis)	5710	6020	6420	7800	10080	3466	3668	4561	5060	6380
	Acceleration along axial direction (Y-axis)	11000	11680	12520	15070	20170	7550	7870	9960	10740	13730
	Acceleration along tangential direction (i.e. Z-axis)	4015	4143	4440	5170	6510	3013	3124	3778	4122	5050
	Resultant acceleration	13027.83	13777.78	14753.99	17739.05	23469.45	8837.07	9227.70	11587.82	12567.50	15959.94

Table 4.6: Vibrations values for the unfinished (i.e. hobbed) and AFF finished gear pair at 1600 rpm.

Type of RMS value	Acceleration measurement direction	Percentage load (%)					Percentage load (%)				
		No load	15%	30%	45%	60%	No load	15%	30%	45%	60%
		Values for the unfinished gear pair (mm/s^2)					Values for the AFF finished gear pair (mm/s^2)				
RMS value of vibrations at GMF	Acceleration along radial direction (i.e. X-axis)	1451	1516	2033	2251	2006	224.3	272.8	483	697	731
	Acceleration along axial direction (Y-axis)	1399	1718	1985	2474	2997	1191	1464	2123	2443	2807
	Acceleration along tangential direction (i.e. Z-axis)	2120	2184	2593	2723	2348	500	503	777	862	917
	Resultant acceleration	2925.24	3165.38	3846.68	4313.05	4303.39	1311.03	1571.85	2311.74	2682.74	3042.12
RMS value of overall vibrations	Acceleration along radial direction (i.e. X-axis)	7960	8290	9090	9890	11730	5630	5830	6970	8160	9020
	Acceleration along axial direction (Y-axis)	16440	17380	18700	20350	24990	11670	12600	14870	17450	19290
	Acceleration along tangential direction (i.e. Z-axis)	6360	6590	7070	7430	8300	5240	5660	6400	7200	7770
	Resultant acceleration	19341.2	20352.3	21961.4	23814.6	28826.7	13976.5	14992.8	17625.4	20565.2	22667.9

Table 4.7: Values of surface roughness, microgeometry errors and resultant vibrations for helical gear pair.

		Roughness parameters		Microgeometry errors (μm)				RMS values of resultant vibrations (mm/s^2)				
		Avg. roughness R_a (μm)	Maximum roughness depth R_{max}	Total profile error F_a (μm)	Total lead error F_b	Total pitch error F_p	Radial runout F_r (μm)	Speed	400 rpm	800 rpm	1200 rpm	1600 rpm
								Load(%)	Resultant overall vibrations			
Unfinished gear pair	Pinion	0.77	6.58	658.2 (DIN12)	93.85 (DIN 12)	833.75 (DIN 12)	1120 (DIN 12)	0	2276.06	7984.39	13027.83	19341.2
								15	2233.02	8417.06	13777.78	20352.3
								30	2356.48	9381.28	14753.99	21961.4
								45	2452.73	10703.21	17739.05	23814.6
								60	2431.37	11388.44	23469.45	28826.7
	Gear	1.99	14.01	266.85 (DIN 12)	86.9 (DIN 12)	647.95 (DIN 12)	982.4 (DIN 12)		Resultant vibrations at GMF			
								0	298.84	529.54	257.7	2925.24
								15	295.21	514.39	271.3	3165.38
								30	263.54	630.17	252.8	3846.68
								45	311.94	774.46	248	4313.05
								60	318.27	774.79	317.5	4303.39
AFF finished gear pair	Pinion	0.48	5.68	384.55 (DIN 12)	96.7 (DIN 12)	454.95 (DIN 12)	656.9 (DIN 12)	0	252.02	308.33	290.12	1311.03
								15	221.83	352.82	288.10	1571.85
								30	196.8	424.58	509.26	2311.74
								45	203.99	518.85	578.30	2682.74
								60	192.77	530.09	844.31	3042.12
	Gear	1.62	10.67	244.1 (DIN 12)	70.5 (DIN 12)	496.75 (DIN 12)	872.6 (DIN 12)		Resultant overall vibrations			
								0	2472.08	6156.22	8837.07	13976.5
								15	2622.57	6957.08	9227.70	14992.8
								30	2733.83	8530.27	11587.82	17625.4
								45	2755.25	9708.34	12567.50	20565.2
								60	2662.75	10707.75	15959.94	22667.9

4.5 Comparison of RMS Value of Vibrations at GMF

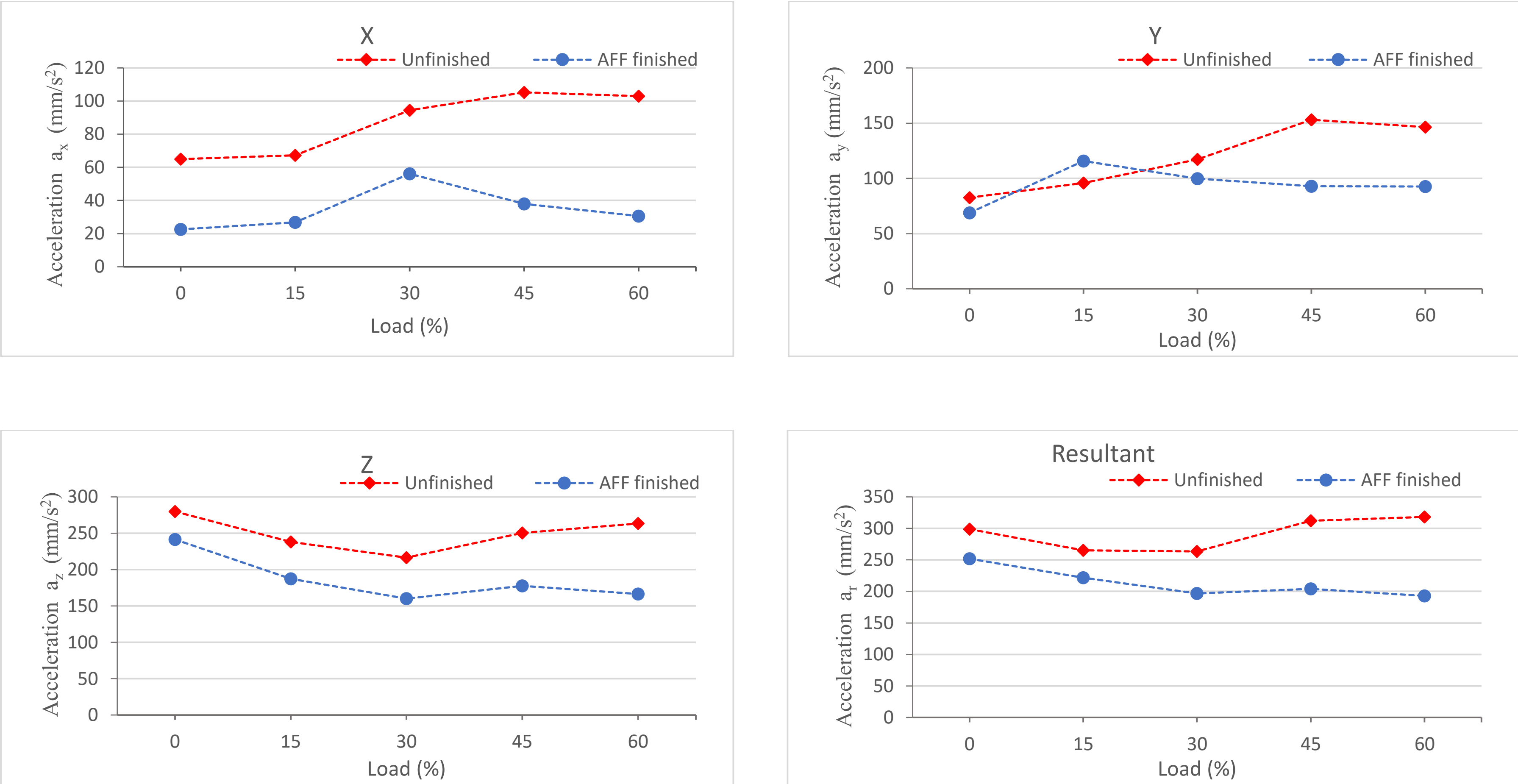


Fig. 4.2: Comparison of RMS value of vibrations at GMF of unfinished (i.e. hobbed) gear pair with finished gear pair at 400 rpm.

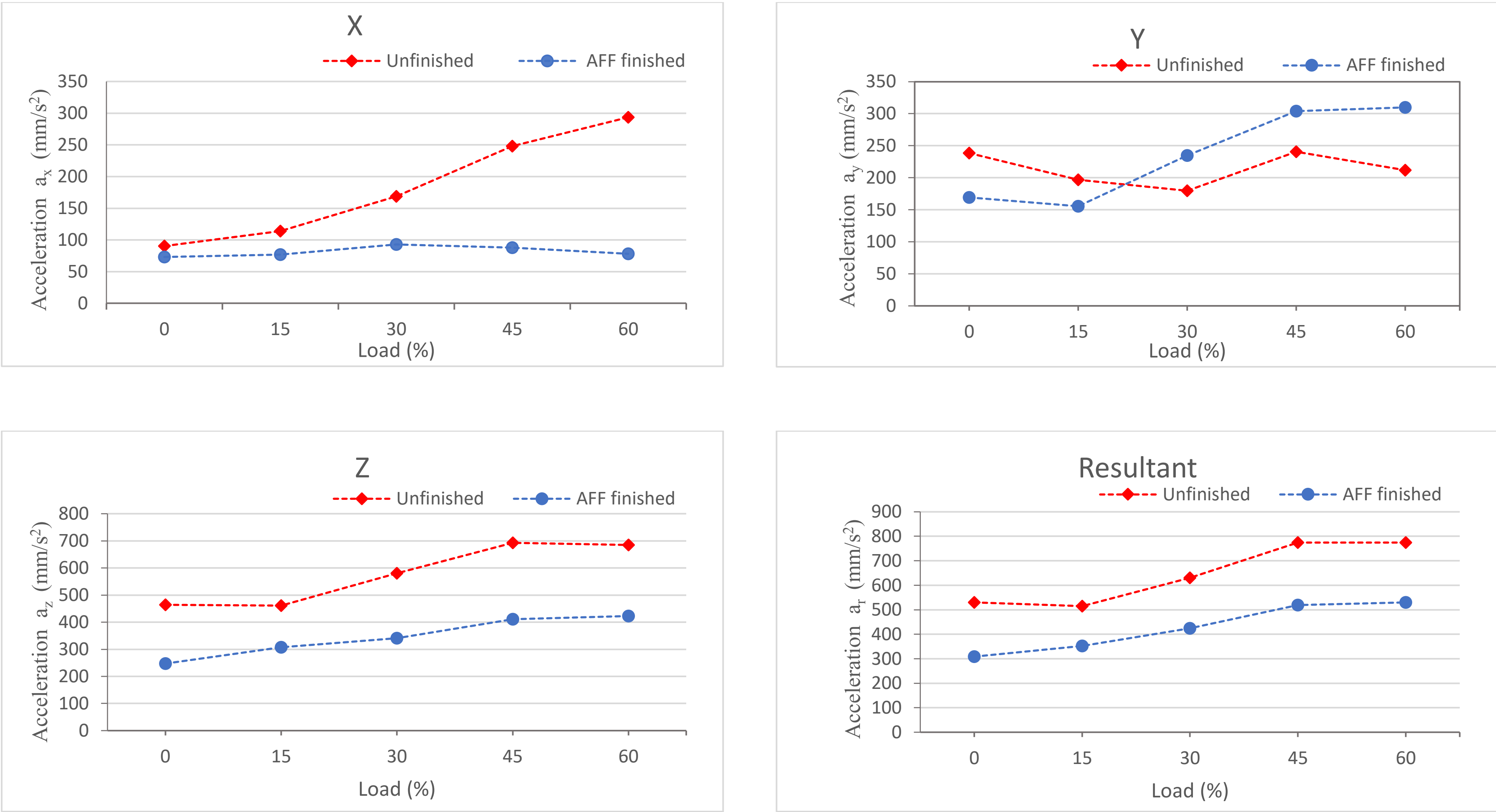


Fig. 4.3: Comparison of RMS value of vibrations at GMF of unfinished (i.e. hobbed) gear pair with finished gear pair at 800 rpm.

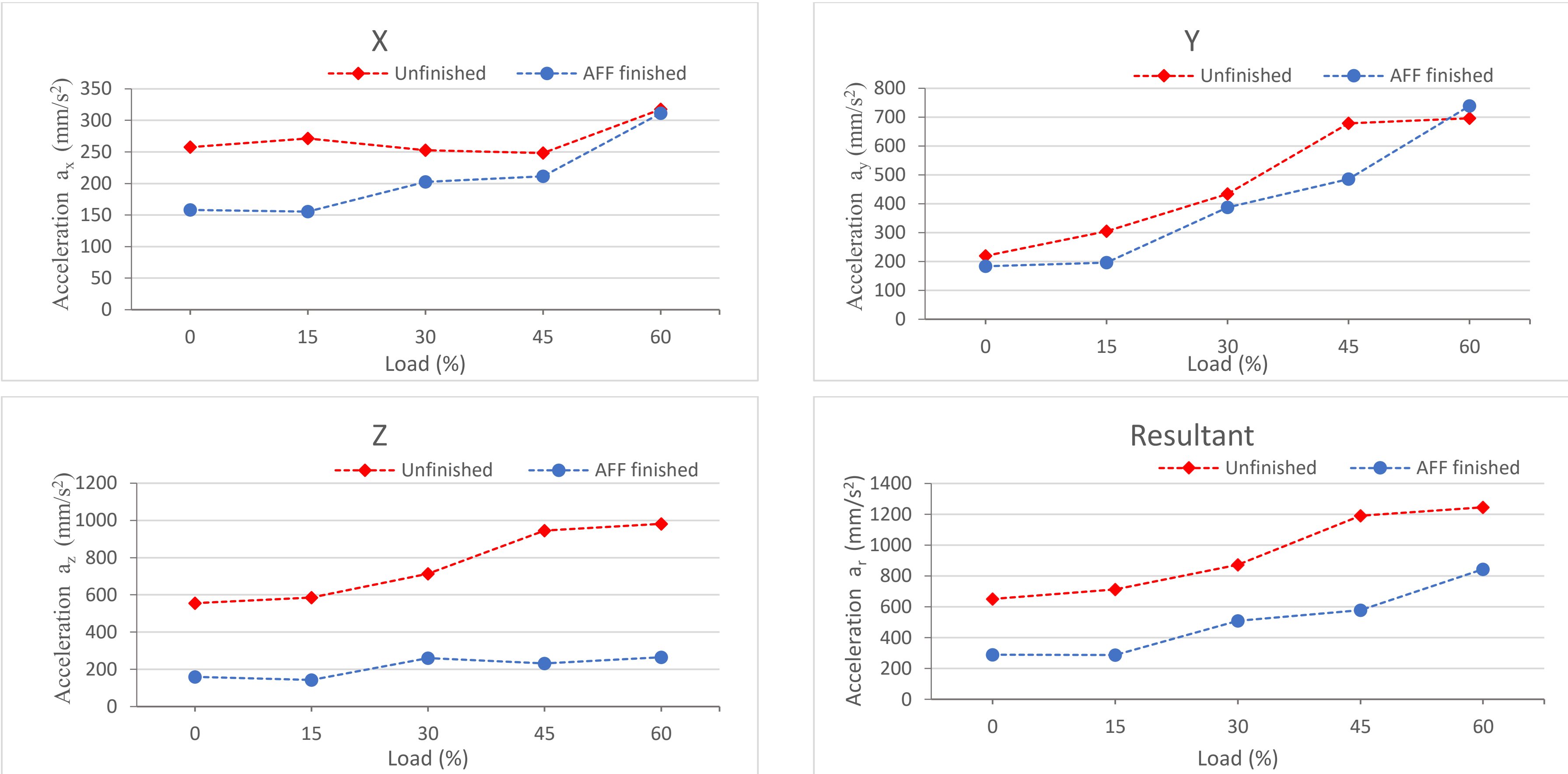


Fig. 4.4: Comparison of RMS value of vibrations at GMF of unfinished (i.e. hobbed) gear pair with finished gear pair at 1200 rpm.

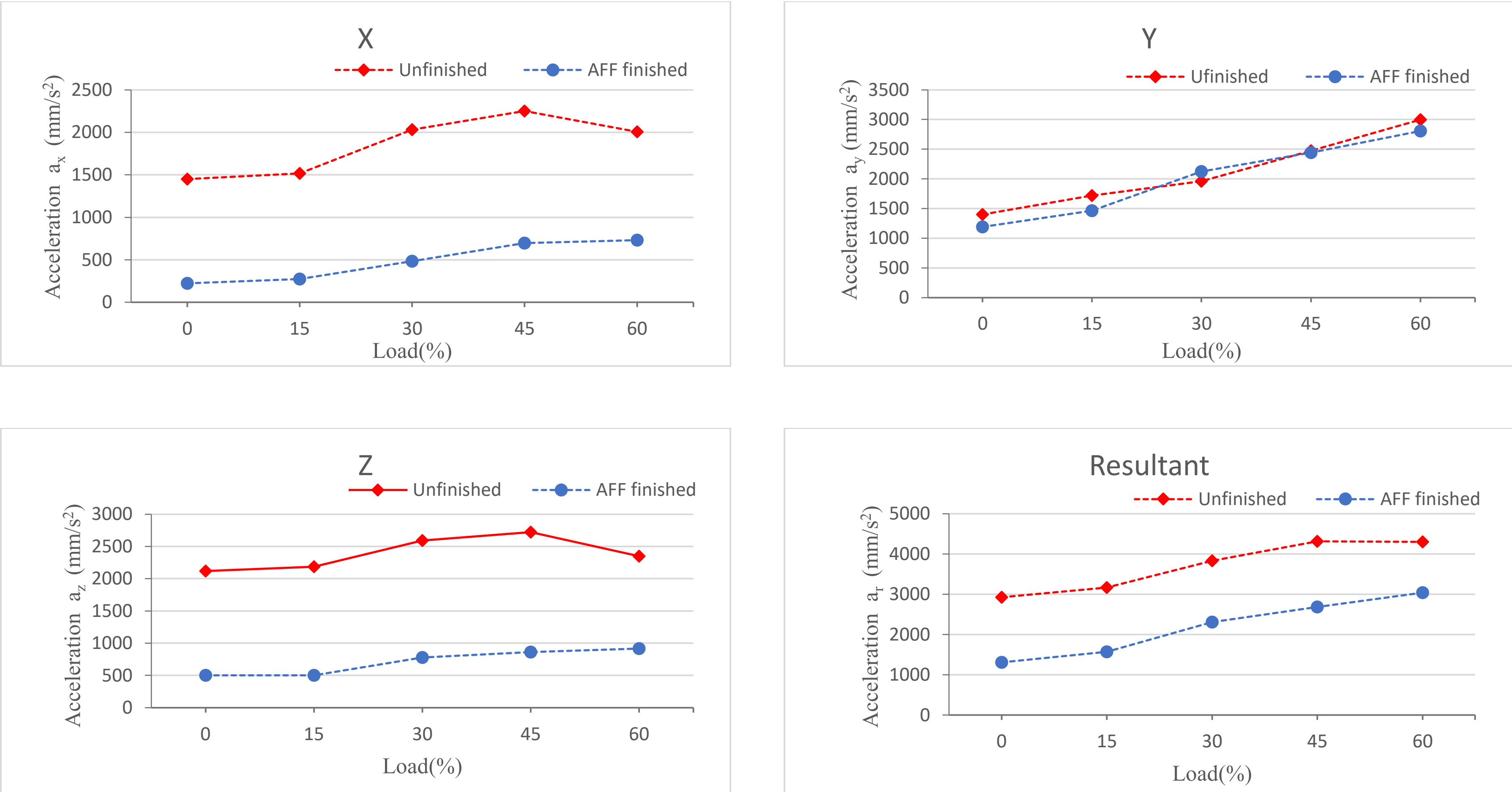


Fig. 4.5: Comparison of RMS value of vibrations at GMF of unfinished (i.e. hobbed) gear pair with finished gear pair at 1600 rpm.

4.6 Comparison of RMS Value of Overall Vibrations at various Speeds and Loads

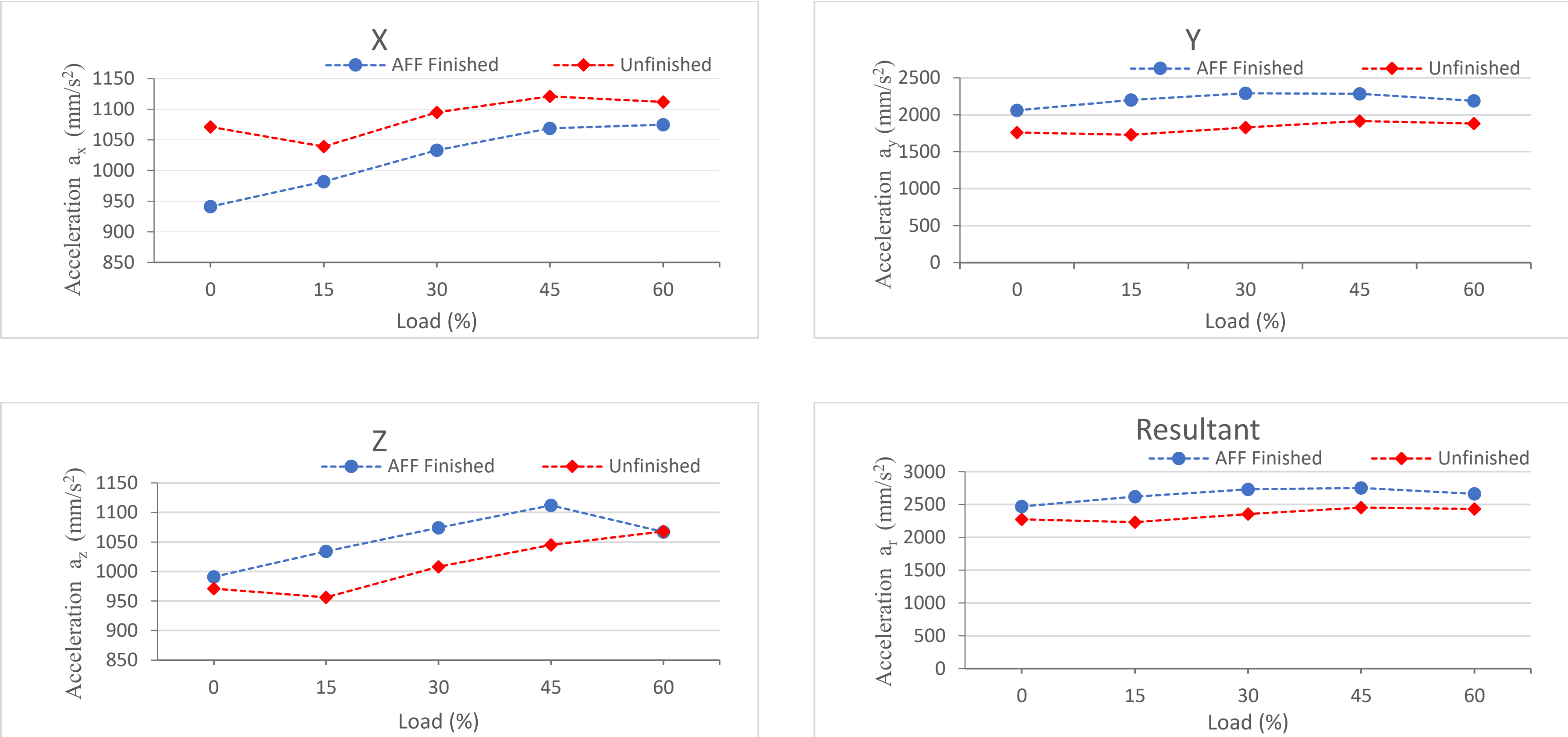


Fig. 4.6: Comparison of RMS value of overall vibrations of unfinished (i.e. hobbed) gear pair with finished gear pair at 400 rpm.

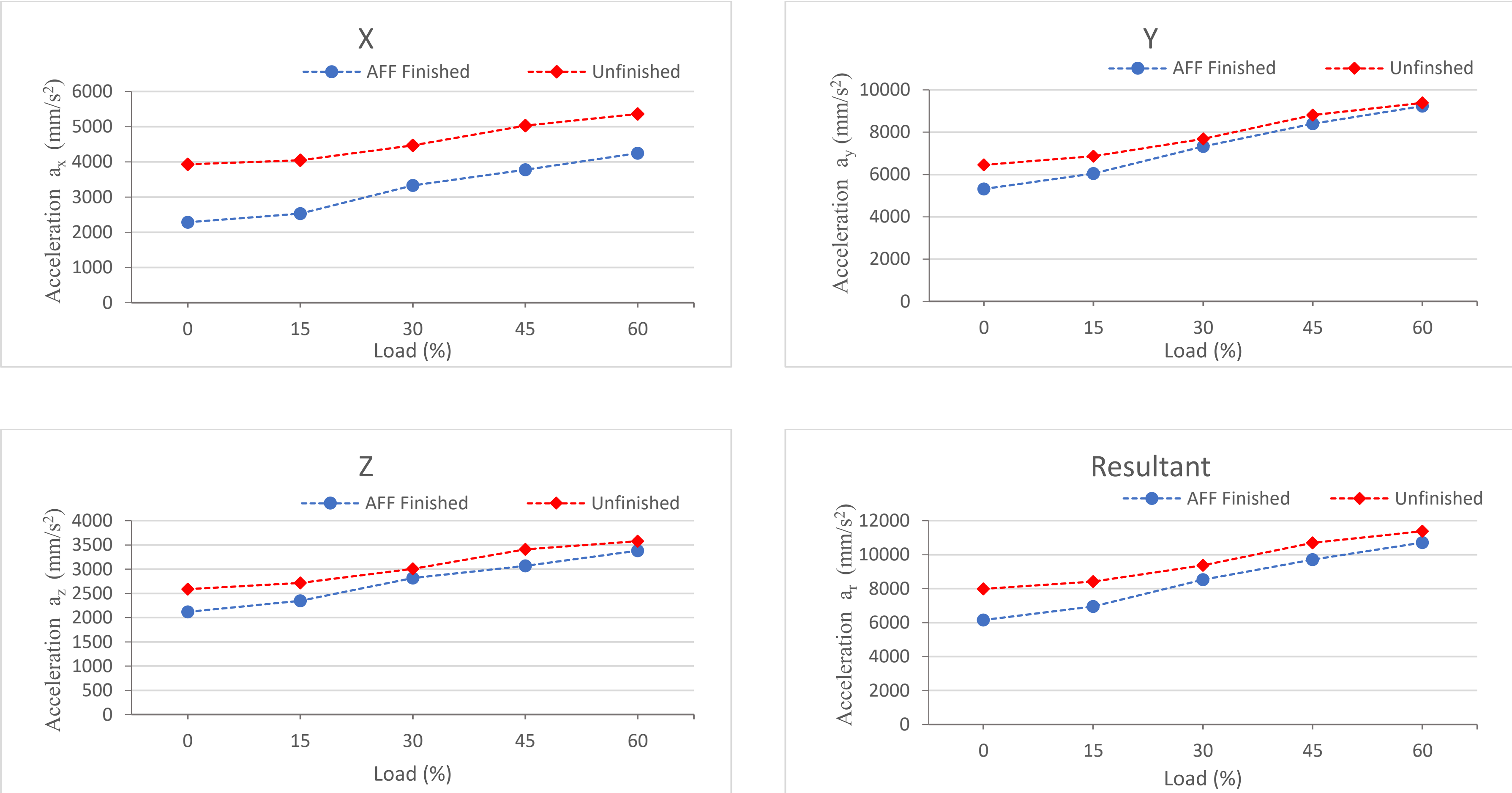


Fig. 4.7: Comparison of RMS value of overall vibrations of unfinished (i.e. hobbed) gear pair with finished gear pair at 800 rpm.

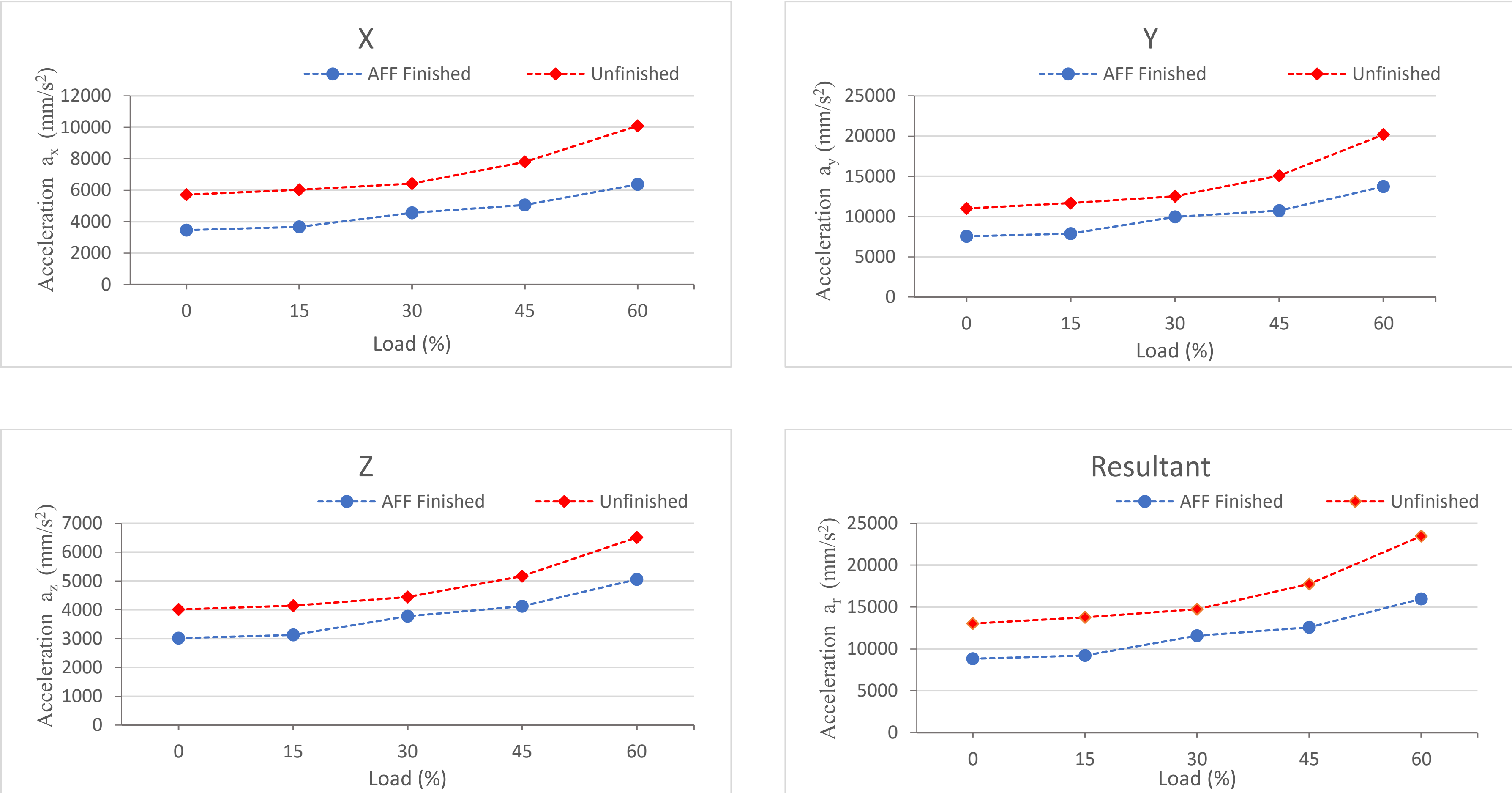


Fig. 4.8: Comparison of RMS value of overall vibrations of unfinished (i.e. hobbed) gear pair with finished gear pair at 1200 rpm.

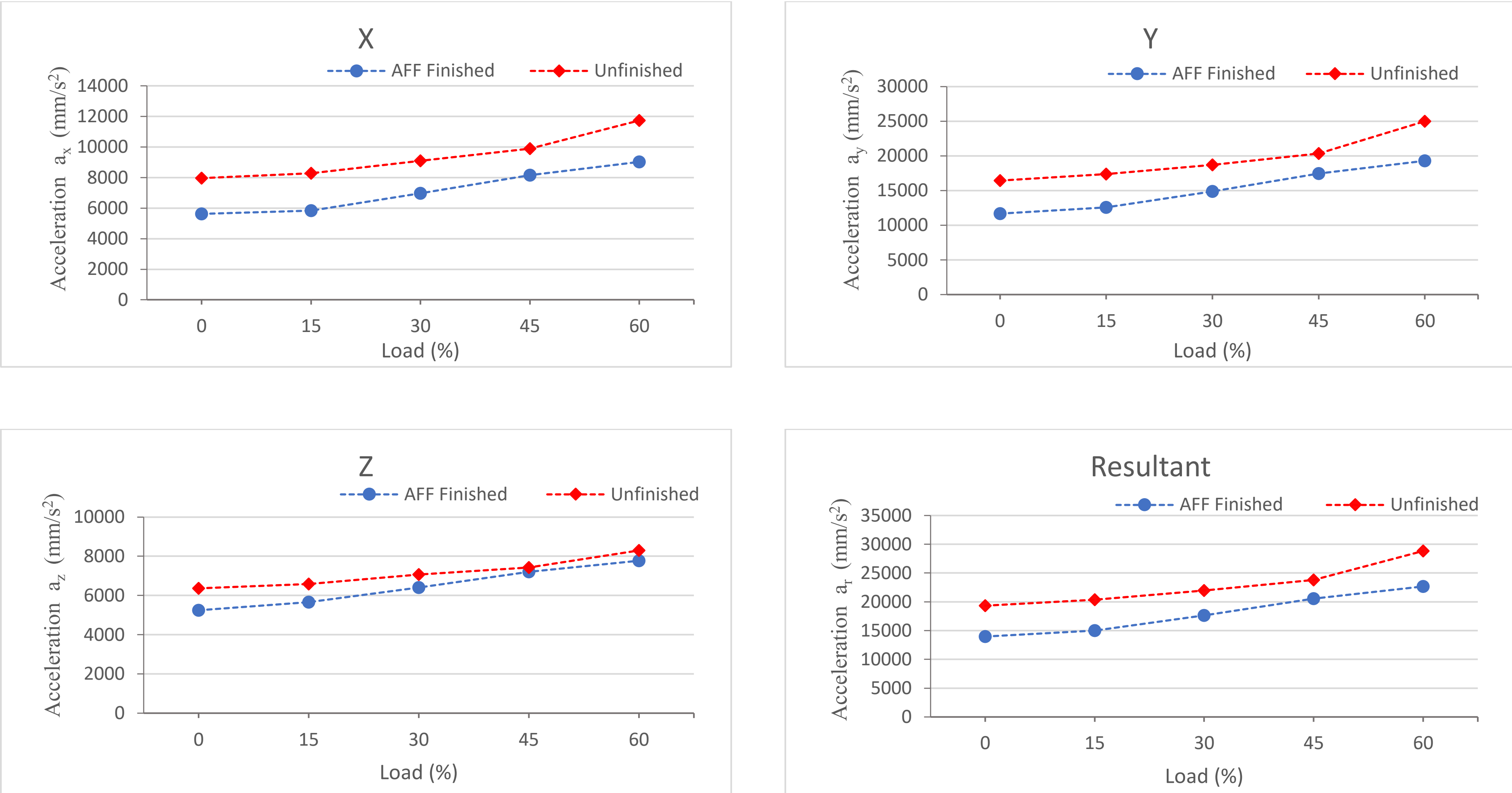


Fig. 4.9: Comparison of RMS value of overall vibrations of unfinished (i.e. hobbed) gear pair with finished gear pair at 1600 rpm.

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4.7 Results for Measurement of Noise

The measured sound pressure level is shown in Table 4.8 and comparisons between sound pressure level of unfinished (i.e. hobbed) and finished gear pair for different speeds and applied loads is shown in Fig. 4.10. Following conclusions are made after analysing the results:

- The minimum noise was produced at speed 400rpm and no load in both conditions i.e. unfinished (i.e. hobbed) gear pair (69.4dBA) and finished gear pair (68.5 dBA).
- The maximum noise was produced at speed 1600rpm and 60% load in both the conditions i.e. unfinished (i.e. hobbed) gear pair (86.4dBA) and finished gear pair (85.4dBA).
- The maximum difference in sound pressure level was 3.4 dBA at the speed of 1200rpm and 15% load.
- Unfinished (i.e. hobbed) gear pair produced more noise than finished gear pair in all load conditions for each speed.

Table 4.8: RMS value of sound pressure level(dBA) with speed and load variations for unfinished (i.e. hobbed) gear pair and AFF finished gear pair.

Load (%)	**400 rpm**		**800 rpm**		**1200 rpm**		**1600 rpm**	
	Unfinished	AFF finished	Unfinished	AFF finished	Unfinished	AFF finished	Unfinished	AFF finished
No load	**69.4**	**68.5**	78.6	77.4	81.7	79.4	83.4	82.3
15%	69.5	68.7	78.9	77.4	**82.6**	**79.2**	84.1	82.6
30%	69.8	68.9	80.1	78.7	82.7	80.5	84.8	83.9
45%	70.2	69.2	81	78.6	83.6	81.6	**85.3**	**85.3**
60%	70.4	69.7	81.5	79.6	85.6	82.4	**86.4**	**85.4**

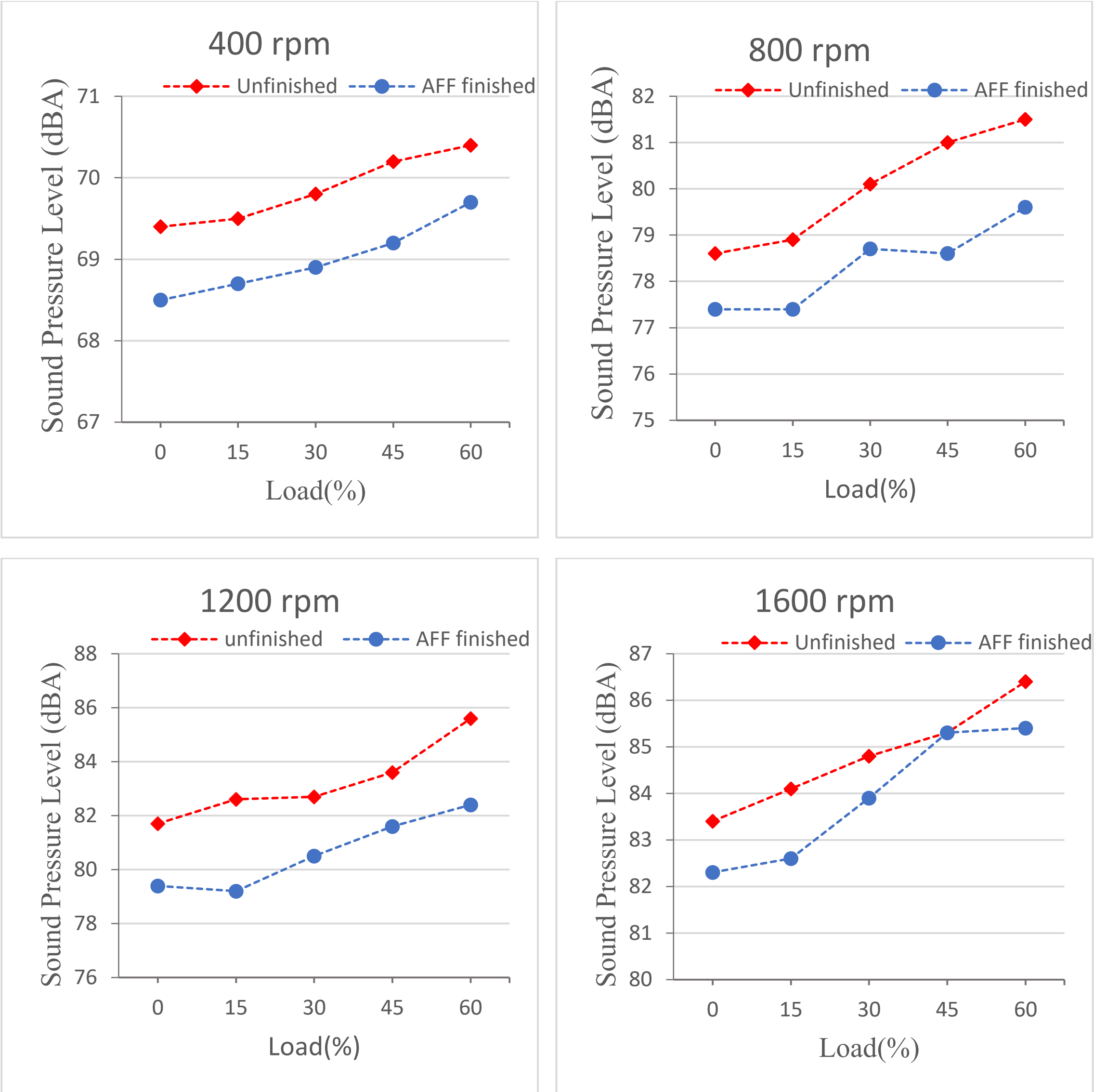

Fig. 4.10: Comparison of the sound pressure level of unfinished (i.e. hobbed) gear pair with finished gear pair at different speeds and loads.

Chapter 5

Conclusions and Scope for the Future Work

This chapter concludes the results of the present work and discusses the scope for the future work.

5.1 Conclusions

Following conclusions are made from the current research work.

- After finishing by AFF process, reduction in microgeometry errors and surface roughness is observed.
- Unfinished gear pair produced more noise as compared to finished gear pair at all conditions of load and speed.
- Vibration at GMF is deceased after finishing but overall vibration may increase at some speeds due to vibration of other elements of gear box.
- Minimum noise produces at low speeds and no-load, while maximum noise produces at high speeds and high-load conditions for unfinished and finished gear pairs.

5.2 Scope for the Future Work

Present work compares noise and vibration levels of unfinished (i.e. hobbed) gear pair with AFF finished gear pair. Other advance finishing processes can also be used for finishing gears. And hence scope for the future work can be summarized as:

- Comparisons between various advance finishing processes and conventional finishing methods such as grinding, shaving and honing can be made and analyzed as an extension to the present work.
- Comparisons of noise and vibration levels of unfinished (i.e. hobbed) gear pair can be made with a gear pair finished by any advance finishing processes other than AFF.
- Find analytic or semi-empirical relationship of level of noise and vibration with microgeometry errors and surface finish of gear.
- Find effect of different tooth profile modifications such as crowning, achieved with the help of advanced finishing processes on noise and vibration levels of gears.

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