Analysis and Comparison of Noise and Vibration of Straight Bevel Gears Finished by Advanced Processes

M.Tech. Thesis

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Candidate's Declaration

I here by certify that work which is being presented in the thesis entitled **Analysis and Comparison of Noise and Vibrations of Straight BevelGears Finished by Advanced Process**in the partial fulfilment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY**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 July 2015 to May 2017 under the supervision of **Prof.Neelesh Kumar Jain,** and**Dr. Anand Parey** of Discipline of Mechanical Engineering.

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

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

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Acknowledgement

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Last, but not the least, I would like to dedicate this thesis to my **Grandfather,** my **Parents**, **Brothers**, my dearest friend **Niranjan Kumar** and his family, **Members of Bruno's house** and **my Friends**, for their love, patience, and understanding, because without their support, I would have never reached where I am today.

(Rahul Kashyap)

Dedicated

To

My Family& Friends

ABSTRACT

Gears are toothed wheels used for the transmission of power in many mechanical systems. Gears are typically used for short distance power transmission. They are compact and have efficient and smooth transmission of power and/or motion between two parallel shafts (e.g. spur and helical gears), intersecting shafts (e.g. bevel gears) or non-parallel non-intersecting shafts (e.g. hypoid gears and worm and worm wheel).

Bevel gears is a cone-shaped gear which transmits power between two intersecting axels/shafts. Performance characteristics of a gear include its load carrying capacity, service life, operating performance, surface characteristics, wear characteristics, transmission characteristics and noise-vibration generation characteristics.

The noise and vibration caused by the rotation of the gears is considered a big problem especially at high loads and speeds. However, since noise and vibration problems tend to happen due to several causes in combination. The following are causes of noise and vibration; Gear material, Gear design, alignment of the shafts on which gears are mounted, Configuration of the gear box, Surface damage to the gears during their manufacturing (finishing, heat treatment and other processing), Surface finish of flank surfaces of the gear teeth, Errors in microgeometry of gear teeth such as errors in their form (i.e. tooth profile, lead), location errors (i.e. pitch and runout), and topography, Accuracy in assembly of gears, Operating conditions such as temperature, friction, running speed, type of unexpected load, type of lubrication, use of coolant, Wear of gears.

Surface characteristics has two major components namely (i) surface quality which includes surface finish, micro-geometry (i.e. form and location errors) and wear characteristics; and (ii) surface integrity that encompasses microstructure, micro-hardness and residual stress. In which surface quality and surface integrity of gears depends on finishing of the gears.

Here we have done analysis and comparison of noise and vibrations of bevel gears finished by some advanced processes viz. electrochemical honing (ECH), pulsed-electrochemical honing (PECH) with unfinished gear. It has been noted that gears which have better finish results have low level of noise and vibrations.

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Chapter 1

Introduction

1.1 Introduction to Gears

Gear is a rotating element having teeth cut on its periphery which mesh with teeth of another gear or cogwheel to transmit torque and/or motion or to change direction of motion. Two or more gears working in tandem are called a gearing system and can produce a mechanical advantage through a gearing ratio which causes engaging gears having different number of teeth to have different speed of rotation and toque. Main advantage of a gearing system is that the teeth of the engaging gears prevent slipping while transmitting torque and/or motion. A gearing system can change the speed, magnitude and direction of a power source. Generally, a rotating gear meshes with another rotating gear however it can mesh with a non-rotating toothed part also such as rack thus producing translation instead of rotation.

1.2 Classification of Gears

Gears can be classified into different categories based on several criteria:

- According to position of axes of revolution
  - Parallel shaft
    - ❖ Spur gear
    - ❖ Helical gear
  - Intersecting shafts
    - ❖ Straight bevel gear
    - ❖ Mitre gear
    - ❖ Spiral bevel gear
  - Non-parallel non-intersecting shaft
    - ❖ Screw gear
    - ❖ Worm and worm wheel
- According to the type of gearing
  - ❖ Internal gear
  - ❖ External gear
  - ❖ Rack and pinion
- According to the tooth profile on the gear surface

Spur Gear

Helical Gear

Internal Gear

Straight Bevel Gear

Spiral Bevel Gear

Miter Gear

Worm Gear

- ❖ Gears with straight teeth
- ❖ Gears with curved teeth
- ❖ Gears with inclined teeth

- According to the peripheral velocity of gears
  - ❖ Low velocity gears (< 3 m/s)
  - ❖ Medium velocity gears (< 3-15 m/s)
  - ❖ High velocity gears (>15 m/s)

1.3 Manufacturing Processes for Gears

Gears can be manufactured by different manufacturing processes of subtractive (i.e. machining), deforming and primary forming types as shown in Fig. 1.1. Type of manufacturing process to be used depends on material, size, type, surface finish, microgeometry, requirements for transmission of torque and/or motion, and operating environment of the gear and productivity and economics of the process.

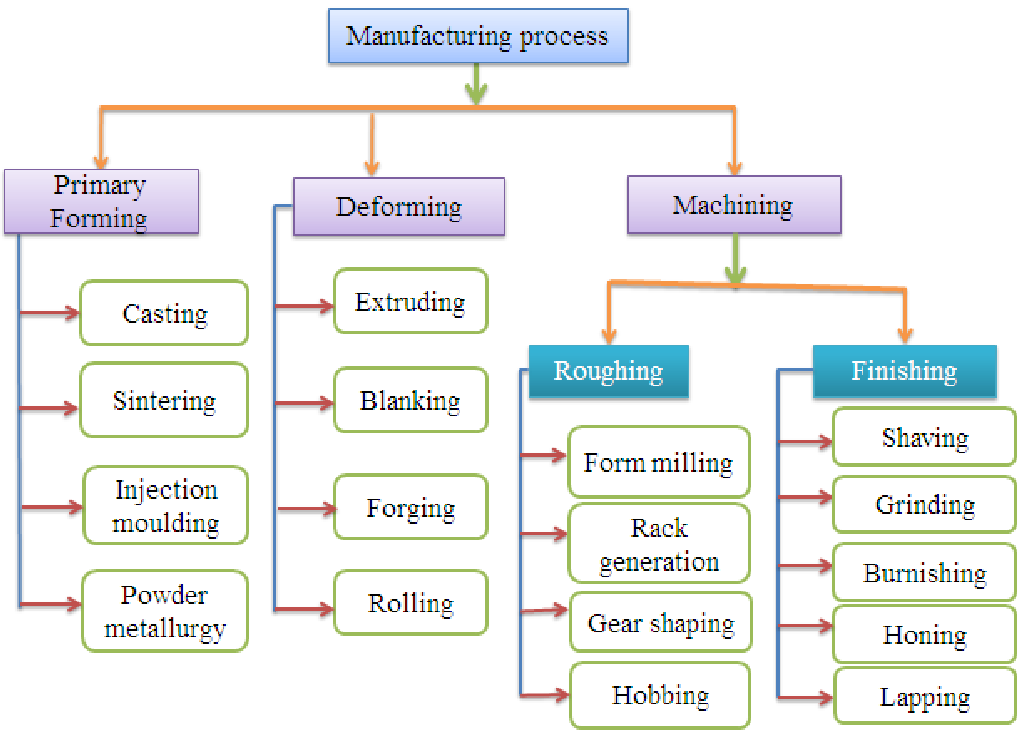


Figure 1.1: Different manufacturing processes for gears.

1.4 Introduction to Conical Gears

Conical gears are used to transmit motion and/or power between two intersecting shafts. They are manufactured from the conical blanks gears. Bevel gears are the most commonly used conical gears. Miter gears are special type of bevel gears which are used to transmit motion between two shafts perpendicular to each other without changing their speed of rotation i.e. direction of drive is changed by 90 degrees. A good example is the mechanism in a hand drill in which rotation of handle of the drill a vertical direction is changed to rotation of the chuck in horizontal direction by bevel gears. Different types of conical gears are mentioned below:

1.4.1 Types of Conical Gears

(A) Straight Bevel gears

- Simplest types of bevel gears
- The meshing gears have line contact
- Not smooth in operation; generate more vibrations and noise at high speed

(B) Spiral Bevel gears

- These gears have curved oblique teeth in the form of spiral which allow engagement between the teeth to develop gradually and smoothly
- They have more contact length and area and less power transmission efficiency as compared to straight bevel gears
- Useful for high-speed applications and applications requiring less noise and vibrations
- Difficult to design and costly to manufacture

(C) Zerol Bevel gears

- These gears are special case of spiral bevel gears having curved teeth with zero spiral angle so that the ends of the teeth align with the axis

(D) Hypoid Bevel gears

- They are used to transmission of power between two non-intersecting and non-parallel shafts
- Their pitch surface is hyperploid rather than conical
- Power transmission efficiency is poor as compared to other straight and spiral bevel gears

1.5 Noise and Vibrations in Gears

Being the rotating element of any equipment, device or machine, gears or their assembly generally produce vibrations that inherent to the gears and are amplified due to defects and errors in their geometry and assembly. Errors induced during manufacturing of gears can be eliminated or reduced during their finishing. However, sometimes it may introduce some errors in microgeometry and surface integrity of the gears which adversely affect their meshing mechanics.

Most of the time, gear noise is not just a problem related to gears only. It might be a system problem and gears can be exciters in the system. Transmission error in the gears is due to variations in geometry of the meshing gear teeth which are source of excitation. Most of the gears used for power transmission purpose are enclosed in the housing. The vibrations generated by such gears are amplified by resonance of the structural elements. This amplification occurs when the speed of the gear is set such that the meshing frequency or a multiple of it is equal to the natural frequency of the system on which the gears are mounted.

1.5.1 Parameters Affecting Noise and Vibrations in the Gears

The following parameters affect noise and vibrations in the gears:

- Gear material
- Gear design
- Design, material and alignment of the shafts on which gears are mounted
- Configuration of the gear box
- Surface damage to the gears during their manufacturing, finishing, heat treatment and other processing
- Surface finish of flank surfaces of the gear teeth
- Errors in microgeometry of gear teeth such as errors in their form (i.e. Tooth profile, lead), location errors (i.e. pitch and runout), and topography
- Accuracy in assembly of gears
- Operating conditions such as temperature, friction, running speed, type of unexpected load, type of lubrication, use of coolant,
- Wear of gears

1.5.2 Methods of Reducing Noise in Gears

The noise and vibration caused by the rotation of the gears is considered to be a serious problem specially at high loads and speeds. Since, gear noise can be happened due to several causes or their combination therefore it is very difficult to identify the exact cause of gear noise. Gear noise can be reduced by following methods or considerations:

- **Using high vibration damping gear material:** Use of higher damping capacity materials such as cast iron for manufacturing gears lowers their noise than that of gears made of other materials. Use of gears with the hub made of cast iron is also more effective.
- **Using plastics as gear material:** Plastic gears are used for light load and low speed applications. Generally, they are quieter during their use but care should be taken to decrease the backlash which is increased by absorption at the elevated temperatures.
- **Using the gears having smaller teeth:** Use of gears having smaller module and larger number of gear teeth helps in reduction of gear noise.
- **Using high-rigidity gears:** Increasing face width of gears and reinforcement of housing and shafts increase rigidity of gears which helps in reducing gear noise.
- **Ensuring correct tooth contact:** Crowning, end relief and profile modification help in avoiding edge contact between the teeth of the meshing gears and eliminating impact on the tooth surfaces. This helps in reducing gear noise.
- **Increasing the contact ratio:** Decreasing the pressure angle and/or increasing the face width results in higher contact ratio which helps in lowering noise level of gears.
- **Increasing the overlap ratio:** Increasing the overlap ratio reduces the gear noise. Consequently, helical gear is quieter than the spur gear and a spiral bevel gear is quieter than the straight bevel gear.
- **Providing appropriate backlash:** A smaller backlash results in pulsating transmission while lager backlash also causes problems therefore appropriate value of backlash should be chosen to minimize gear noise.
- **Eliminating interference:** Chamfering the corner of the top land and modifying the tooth profile help in avoiding interference and smooth meshing of the engaging gears decrease gear noise.
- **High quality finishing of the gears:** Figure 1.2 presents different components of microgeometry errors of a gear and their effects on performance of a gear. High quality of the gears can be ensured by minimizing errors in tooth profile, lead, pitch, runout and topography by proper combination of finishing and surface modification processes.
- **Using gears having better surface quality:** Surface quality of gears including different aspects of surface finish and surface integrity can be improved by proper finishing and/or surface properties enhancing processes. Use of conventional gear finishing processes such as

grinding, lapping and honing or some advanced finishing process and running-in the gears in oil for some duration can also improve the smoothness of tooth surface which helps in reducing the noise.

- **Using the gears that have no dents:** Any dent, dimple or mark on the flank surfaces of gear teeth and making tip of the gears non-involute generates abnormal sounds.
- **Using proper lubrication:** Sufficient lubrication of gears ensuring hydrodynamic lubrication between the meshing gears reduces gear noise. Use of high viscosity lubricant also reduces gear noise.

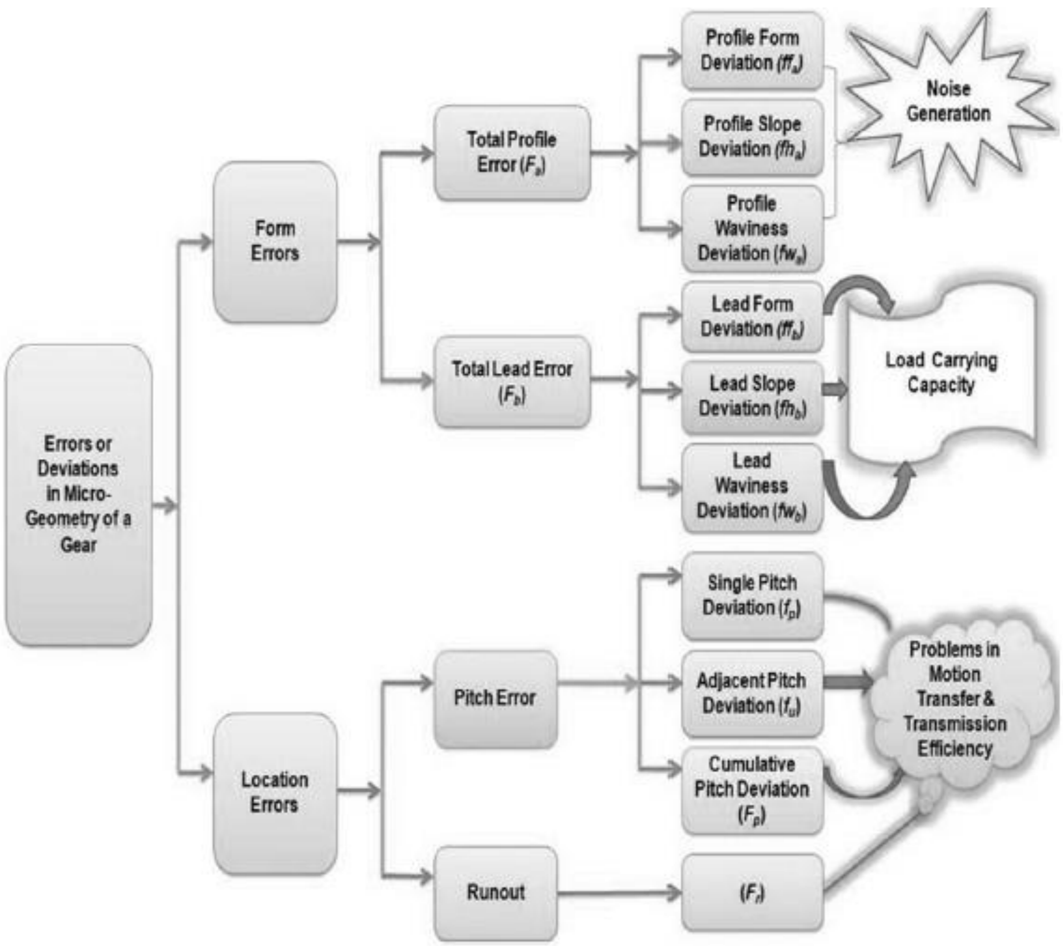


Figure 1.2 different components of microgeometry or form error of a gear and their effects. (**Jain and Petare,** 2016).

1.5.3 Concept of Noise Measurement

Sound pressure or acoustic pressure is deviation of the local pressure caused by a sound wave from the atmospheric pressure. In air, sound pressure can be measured using a microphone, and in water with a hydrophone. The SI unit of sound pressure is the Pascal (Pa).Whenever human beings hear a very loud noise, they experience unpleasant feelings due to pressure caused by the sound wave. Even though this pressure can be measured similar to air pressure but, in practice **acoustic pressure level** or **sound pressure level (SPL)** is a measure of the effective pressure of a sound relative to a reference value or with reference to hearing threshold. Sound pressure level, denoted $\boldsymbol{L_p}$ is defined by

$$L_p = log_e \frac{p}{p_0}(neper); \text{OR} = 2\, log_{10}\left(\frac{p}{p_0}\right)(Bel); \text{OR } = 20\, log_{10}\left(\frac{p}{p_0}\right)(deci\, Bel)$$

Where; p is the root mean square value of sound pressure; and p_0 is the reference pressure for sound. Commonly used reference pressure for sound in air is $p_0 = 20\mu Pa$; which is often considered as the threshold for human hearing. Most of the sound level measurements are made relative to this reference i.e. for $p = 1\ Pa$ gives an SPL of 94 dB. In other media, such as underwater, a reference level of 1 μPa is used.

Sound intensity level (SIL) is the defined as the sound wave power per area. It is a special quantity that allows us to measure the energy of sound or to be more precise, the energy per second per one squared meter.

$$SIL = 10\, log_{10}\left(\frac{I}{I_{ref}}\right)(deci\, Bel)$$

Where, I is the sound intensity in W/m^2; I_{ref} is the reference value of the sound intensity which is typically assumed to be equal to 10^{-12} W/m^2.

While measuring SPL, 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 this distance need not to be quoted because no single source of source is present. Generally, distance of **one metre** 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.

1.6 Finishing of Conical Gears by Conventional Processes

As mentioned in the Section 1.5.2 that high quality finishing of gears and better surface finish and surface integrity of the gears can greatly help in reducing the gear noise. Therefore, main goals of finishing a gear (as mentioned in Fig. 1.3) are (i) to minimize gear noise which can be achieved by reducing microgeometry errors and surface roughness of the gear; and (ii) to maximize load carrying capacity which can be attained by modifying flank surfaces of a gear and improving its surface integrity (**Karpuschewski et al., 2008).**

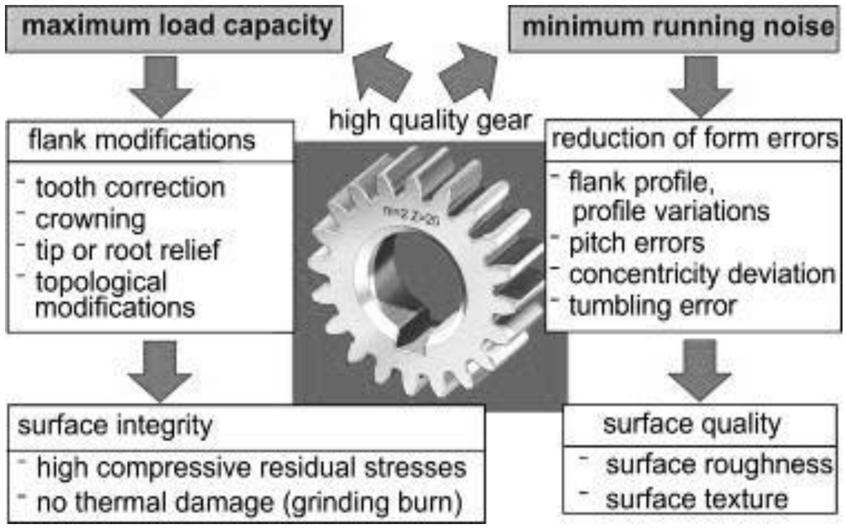


Figure 1.3: Goals of gear finishing (**Karpuschewski et al., 2008**).

Finishing of the bevel gears is very laborious and challenging due to their complex tooth geometry as compared to the cylindrical gears. Gear grinding and gear lapping are the only conventional processes that are used to finish the bevel gears. **Karpuschewski et al. (2008)** have mentioned that use of these processes results in some undesirable side effects. Gear grinding gives following two major undesirable effects: (i) small transverse grind lines on the flank surface which causes noise generation and vibration of the gears; and (ii) grinding burns which damage the surface integrity of the ground gears and can even lead to gear failure due to tooth breakage. Moreover, it is expensive, complicated less productive and requires skilled labor. Whereas, gear lapping finishes gears in a conjugate pair and can eliminate only minute deviations in the micro-geometry. The process is slow thus requiring longer lapping cycles which adversely affects gears micro-geometry. To overcome the aforesaid drawbacks of the conventional finishing processes for the conical gears, development of some novel unconventional finishing processes such as electrochemical honing (ECH) by **Shaikh (2013)**, pulsed electrochemical honing (PECH) by **Pathak (2016)**, abrasive flow finishing (AFF) by **Venkatesh et al. (2014)**, ultrasonic assisted abrasive flow machining (UAAFM) by **Venkatesh et al. (2015)** have been undertaken for high quality of finishing the bevel gears. Following section describes finishing of bevel gears by ECH and PECH Processes.

1.7 Finishing of Bevel Gears by ECH and PECH Processes

Electrochemical honing (ECH) is an advanced finishing process which is combines advantages of electrochemical machining (ECM) and mechanical honing and at the same time overcomes their limitations due to their hybridization. It has been used for high quality finishing of internal cylinders, bushes, bearings and sleeves. It uses for finishing of cylindrical gears started from 1980s. But, finishing of bevel gears by ECH remained unexplored because it requires an arrangement different than one used for finishing of cylindrical gears because bevel gears cannot be moved axially when it is in mesh with pinion. **Shaikh (2013)** was probably the first researcher to explore ECH for finishing of conical gears (i.e. straight bevel gear) by envisaging a novel concept of twin complementary cathode gears as described by **Shaikh and Jain (2016)** and reproduced in Fig.1.4.

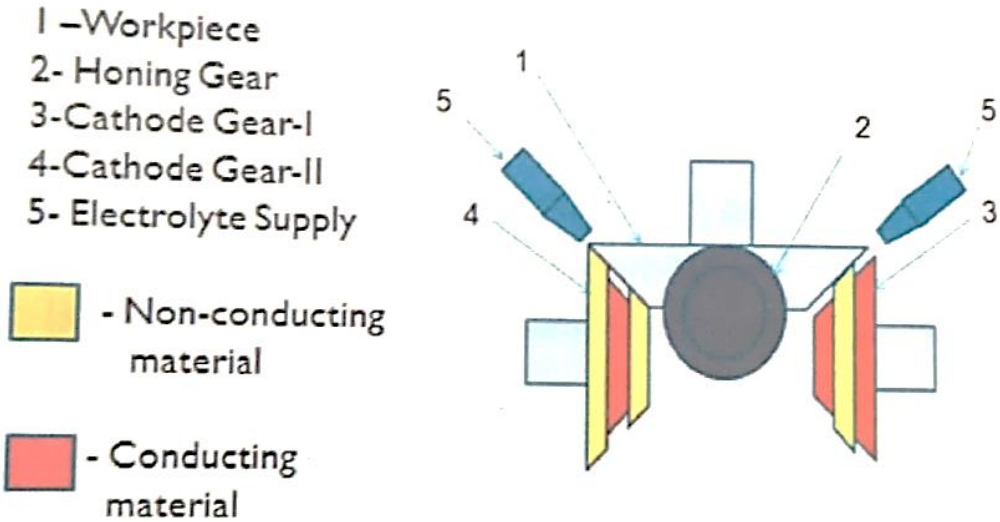


Fig. 1.4: Concept of twin complementary cathode gear for bevel gear finishing by ECH envisaged by **Shaikh and Jain (2016)**.

In gear finishing by ECH, design of cathode and honing gear and their arrangement with respect to the workpiece gear in the finishing chamber depends on geometry of the workpiece gears. For bevel gear finishing by ECH, a honing gear was used to remove the oxide layer from the workpiece gear tooth surface and expose fresh surface. This gear was mounted perpendicular to the cathode and workpiece gears so as to mesh with them as mentioned by **Shaikh and Jain (2016)** and reproduced in Fig. 1.5. **Shaikh and Jain (2013)** have reported 62.7 % improvements in average surface roughness and 32.7 % improvements in maximum surface roughness. They have also reported that quality of gear has improved from DIN 8 to DIN 7 for the adjacent pitch error and DIN 7 to DIN 6 for the runout. **Shaikh and Jain (2016)** have claimed that improvement in surface roughness and micro-geometry of straight bevel gears (i.e. pitch error and runout) will reduce the gear running noise and vibrations.

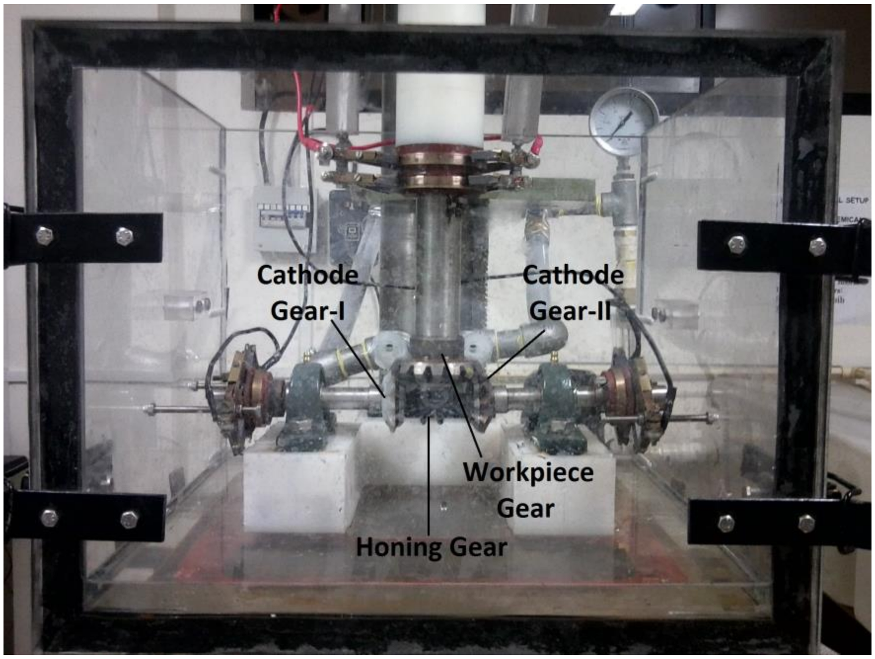
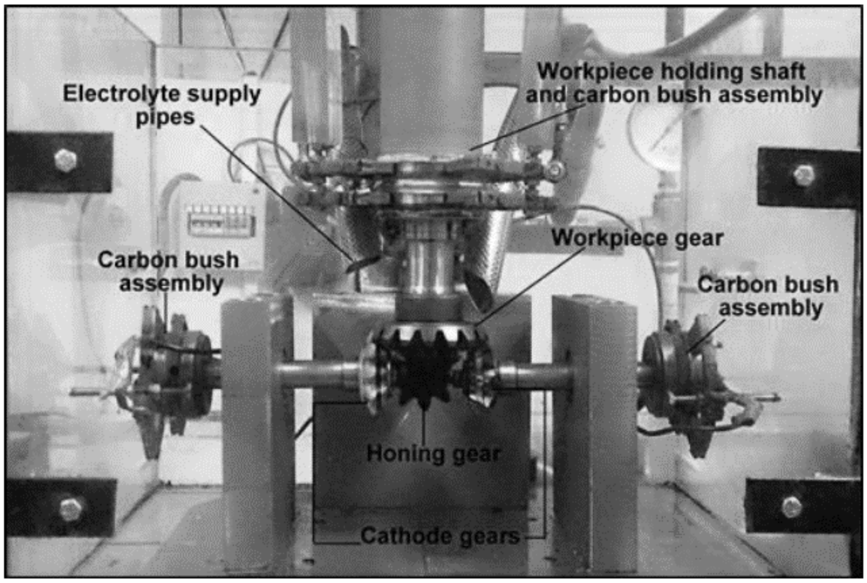
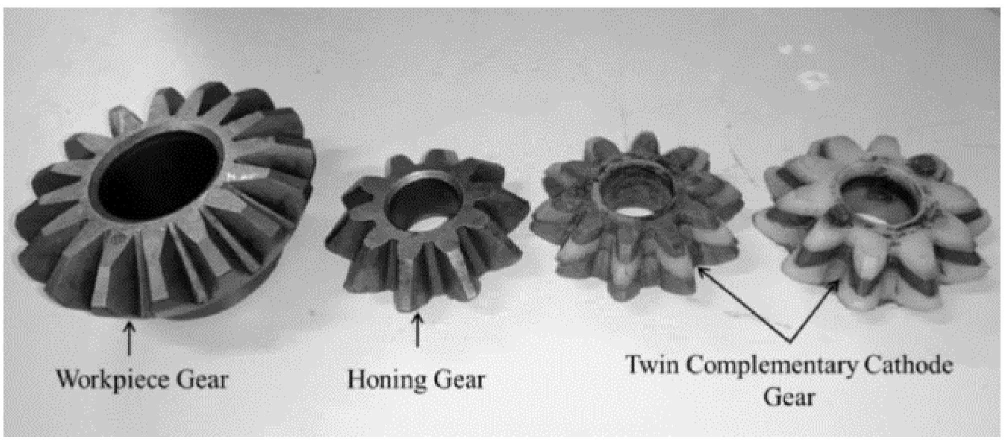


Fig.1.5: Photograph of the machining chamber for ECH of bevel gears reproduced from **Shaikh and Jain (2016)**.

Pulsed electrochemical honing (PECH) is a hybrid finishing process of pulsed electrochemical finishing (PECF) and mechanical honing. PECH process is a modified version of ECH process which uses pulsed DC power instead of continuous DC power. **Pathak (2016)** used PECH for better quality finishing of straight bevel gears than ECH after **Pathak et al. (2015)** proved superiority of PECH over ECH for straight bevel gear finishing. The finishing chamber developed by **Pathak (2016)** is reproduced in Fig. 1.6a along with the photographs of the cathode gears, honing gear and workpiece gear (Fig. 1.6b) used by him.



(a)



(b)

Fig.1.6: (a) photograph of finishing chamber arrangement for straight bevel gear finishing by PECH developed by **Pathak (2016)** and; (b) photograph of workpiece bevel gear, honing gear and complementary cathode gears **(Pathak, 2016).**

Use of pulsed DC power source provides short voltage pulses between anode and cathode causing electrolytic dissolution of the workpiece to occur during the pulse-on time (T_{on}) whose typical value lies in the range from 1 to 7 ms. and more effective flushing away the products of electrochemical reaction from the IEG during the pulse-off time (T_{off}) which typically lies in the range from 2-15 ms. **Pathak et al. (2014)** identified optimum values for pulse-on time, pulse-off time, and finishing time as 2ms, 4.5ms (i.e., duty cycle of 30.77%) and 6 min, respectively. A passivating layer of metal oxide is generated over the workpiece gear tooth due to evolution of oxygen at anode. It prohibits its further dissolution. Thickness of this protective layer is more at valleys as compared to that on the peaks. The honing tool selectively removes this passivating layer enabling more effective electrolytic dissolution. **Pathak et al. (2017)** reported that finishing of bevel gears by PECH improved their quality in DIN standard from 9 to 8 for single pitch deviation; from 10 to 6 for adjacent pitch deviation; and from 8 to 7 for runout. These enhancements in the microgeometry of the best-finished gear improved its overall quality from DIN 10 to 7. They also reported sustainable improvement in the gear tooth flank topology of the PECH-finished bevel tooth flank. **Pathak et al. (2016)** noticed that microstructure of PECH-finished straight bevel gear had defect-free and smoother surface after smoothening of gear cutting marks, scratches and deep grooves. Such flank surface leads to quieter operation, lesser vibrations, reduced wear, increased service life and enhanced tribological fitness of the straight bevel gears. They also reported that PECH is an economical process because it consumes 25% less energy than the ECH process to achieve the same level of finishing.

1.8 Organization of Thesis

Chapter 2 presents review of past work on gear noise and vibrations, effects of gear finishing process on noise and vibrations, the identified research gaps and the research objectives defined to fill the identified research gaps.

Chapter 3 presents design and development of the test rig for noise and vibration analysis of bevel gears along with details of the subsystems of the developed test rig.

Chapter 4 presents noise and vibrations results and their analyses.

Chapter 5highlights the conclusions derived from the present work and scope for future work based on the limitations of the present work.

Chapter 2

Review of the Past Work and Research Objectives

2.1 Past Work on Noise and Vibration of Gears

Very limited research has taken place on minimizing noise and vibration of gears. Most of the past research has been done on minimizing noise and vibrations levels of spur and helical gears and that too focused on transmission error which really increases gear noise and vibrations level. The past research also aimed at decreasing the noise and vibration of gears by flank and profile modifications which are quite complex from theory and processing points of view. Following paragraphs describe the reported past work on reduction of noise and vibrations of the gears:

Liu et al. (1990) performed experiments on spur gear used in the headstocks of the machine tools comparing noise of the gears ground on different gear grinders and reported that gears with better surface finish produced lower noise. They conducted 242 tests in which the maximum and minimum values of noise level were found to be 85dB and 75.7dB respectively. They concluded that gears having lower values of pith error, profile error and transmission error had noise level reduced by 4dB**.**

Akerblom and Parssinen. (2002) studied effects of gear finishing processes on geometry of the gear tooth flanks and noise and vibration of the helical gears. Eleven gear pairs were finished using three finishing processes namely shaving, profile grinding using with CBN-coated steel grinding wheels, and threaded wheel grinding deliberately inducing different errors and surface finishes to the gear pairs. They investigated the relationship between transmission error and gearbox noise and reported that transmission error is an important excitation mechanism for gear noise. Some of their important conclusions are:

- Shaved and ground gears and found that shaved gears do not seem to be nosier than ground gears even if their tooth deviations are larger. Gears ground with threaded wheel grinding may be a little less noisy than profile ground gears.
- A rougher surface finish may increase noise and vibration especially at lower torque.
- Increased lead crowning increases noise and vibration levels.
- Helix angle error increases noise level.

- Pitch errors seem to decrease the gear mesh harmonics and thus decreasing the overall noise and vibration level.

Lewicki et al (2008) tested five different spiral bevel pinion and gear to evaluate noise level of formate spiral bevel gear. Experimental tests were conducted on the OH-58D helicopter main-rotor transmission in the NASA Glenn 500 hp transmission test stand. All tested gears were made using standard aerospace practices in which the surfaces were carburized and ground. The material used for all gears was X-53(AMS 6308). One set of gear design tested was a 62-tooth, spiral bevel gear manufactured using the formate process. The 19-tooth, spiral-bevel pinion was manufactured using the conventional, face-milled grinding process. This gear set was designed to reduce transmission error, vibration, noise and stress as well as to provide proper tooth contact. They observed that the formate spiral bevel design showed a decrease in noise about 5 dB due to improved-bearing-contact and low transmission error as compared to others spiral bevel gear sets.

Zhu et al. (2011) proposed the concept of holey straight bevel gear (schematically depicted in Fig. 2.1) as an alternative to tooth profile modification for reduction of vibrations of straight bevel gear. In the holey straight bevel gear, holes are drilled in teeth of straight bevel gear which can help in improving the stress distribution, reducing the bending stress and prolonging the gear life. They built dynamic models of the holey straight bevel gear by combination of transmission error and mesh impact as the dynamic excitation and applying the acceleration mean square of the dynamic steady state response to express the vibration and noise. They reported that (i) average amplitude of vibration for the ordinary straight bevel gear was found to be 116.39 m/s^2 and 105.02 $m/s^2$for the holey gear implying 9.77% reduction in average amplitude of vibration; (ii) root mean square value of vibration acceleration for the holey straight bevel gear and the ordinary gear were found to be 252.2 m/s^2 and 341.8 m/s^2 respectively revealing reduction by 26.21%.

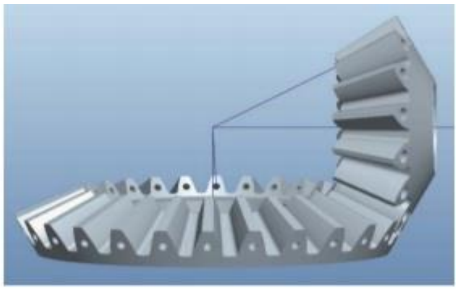


Fig. 2.1: Pro/E model of holey straight bevel gear **(Zhu et al. 2011).**

2.2 Identified Research Gaps

Following research gaps were identified for the present work based on the review of the past work:

- No work has been reported on studying effect of advanced finishing processes on noise and vibration of straight bevel gears.
- No work has been reported on relating the errors in micro-geometry, surface finish and gear quality to noise and vibrations in of straight bevel gears.

2.3 Objectives of the Present Research Work

This is evident from the review of past work that very limited work has been done on noise and vibration analysis of the conical gears. Therefore, present research work was undertaken with major goal to study the effect of surface finish and errors in micro-geometry of straight bevel gears on their noise and vibrations. Following research objectives were identified to accomplish this goal:

- Analysis and comparison of noise and vibration levels of the straight bevel gears finished by following advanced finishing processes:
  - Electrochemical honing (ECH) process
  - Pulsed-ECH (PECH) process
  - Abrasive flow finishing (AFF) process
  - Best finished gear by the most commonly used conventional finishing process
- Design and development of test rig for measurement of noise and vibrations level of the straight bevel gears.
- To find relationship between noise and vibrations of straight bevel gears and their micro-geometry and surface finish.
- To find the most critical parameter of micro-geometry and surface finish which affects running noise and vibration of the straight bevel gears.

Chapter 3

Development of the Test Rig

Analysis and comparison of the noise and vibrations of the straight bevel gears finished by advanced process requires (i) workpiece gear finished by ECH process; (ii) workpiece gear finished by PECH process; (iii) unfinished workpiece gear; (iv) a perfect pinion which meshes properly with workpiece gear.

3.1 Details of the Test Rig

Figure 3.1a depicts the schematic diagram of the top view of the test rig conceptualized for measuring the noise and vibrations of straight bevel gears. Whereas, Fig. 3.1b shows photograph of different equipment used in it. It consists of five major sub-parts: (i) gear box; (ii) supporting structure; (iii) noise and vibrations analyzer for gears; (iv) motion providing system; and (v) speed controlling system.

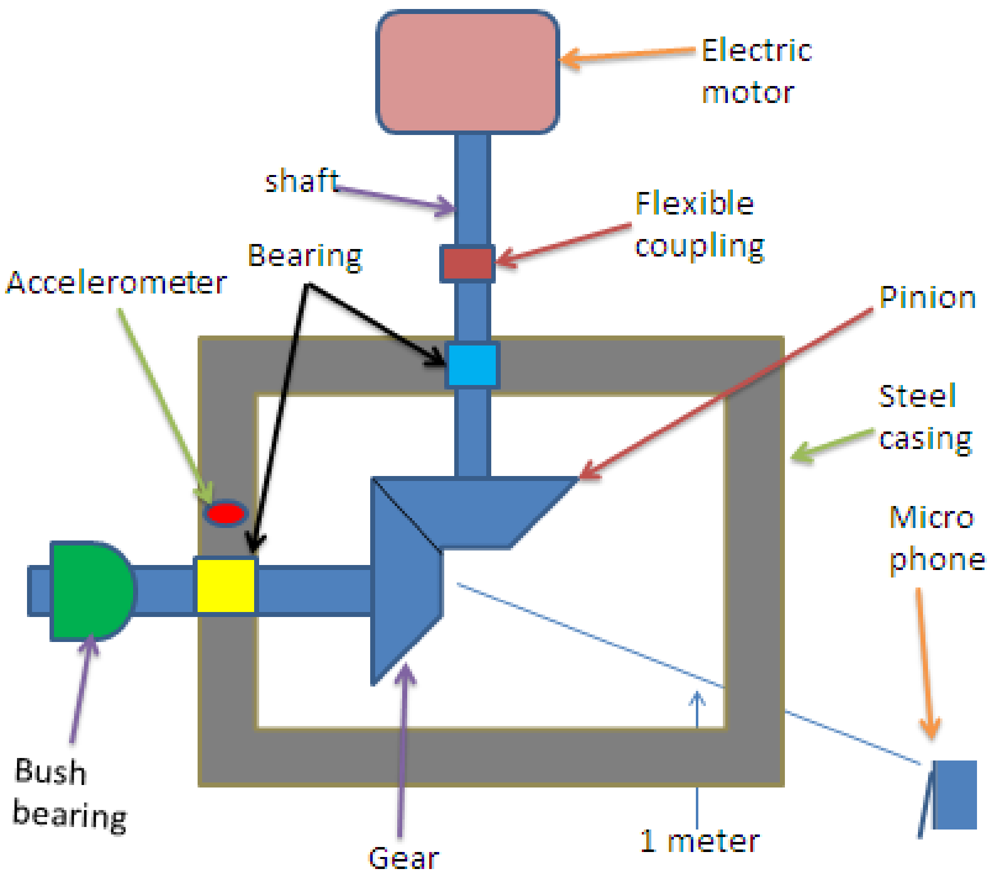


Fig. 3.1a

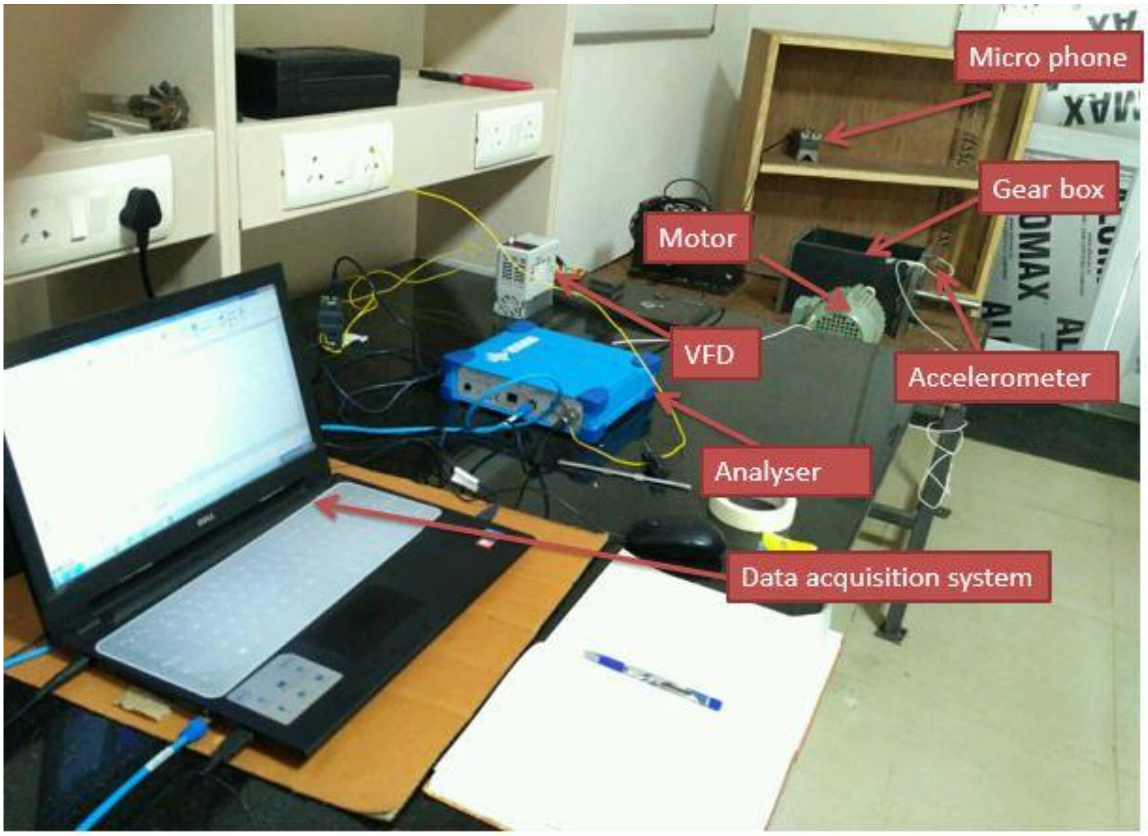


Fig. 3.1b

Fig. 3.1: (a) Schematic diagram of top view of the test rig conceptualized for measuring noise and vibrations of the straight bevel gears; and (b) photograph of different equipment used in it.

3.2 Subsystems of the Test Rig

3.2.1 Gear Box and its Fabrication

Fig 3.2 Photograph of the designed and developed gear box which consists of workpiece gear, pinion and mounting elements for these gears. Deep grove ball bearings (6205) of stainless steel, as shown in Fig 3.3, were used to mount and support medium carbon steel shafts on which gear and pinion were mounted. This type of bearing produces fewer vibrations and lesser noise at higher speed. It can take both radial and axial load. Bush bearings as shown in figure 3.4 were used to support the output shaft on which workpiece gear was mounted to prevent the deflection of output shaft. Mild steel rectangular plates of thickness 16 mm were used for gear box casing and to support and mount the bearings due to its better vibration damping quality and higher strength-to-weight ratio. Figures 3.5 and 3.6 present (a) drawing and (b) photograph of the shafts used to mount the workpiece gears and pinion.

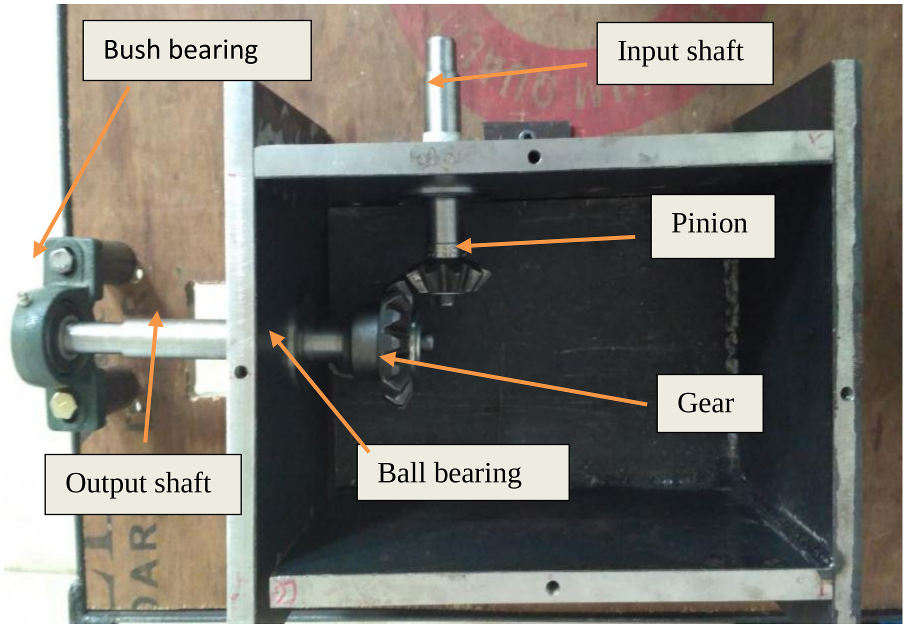
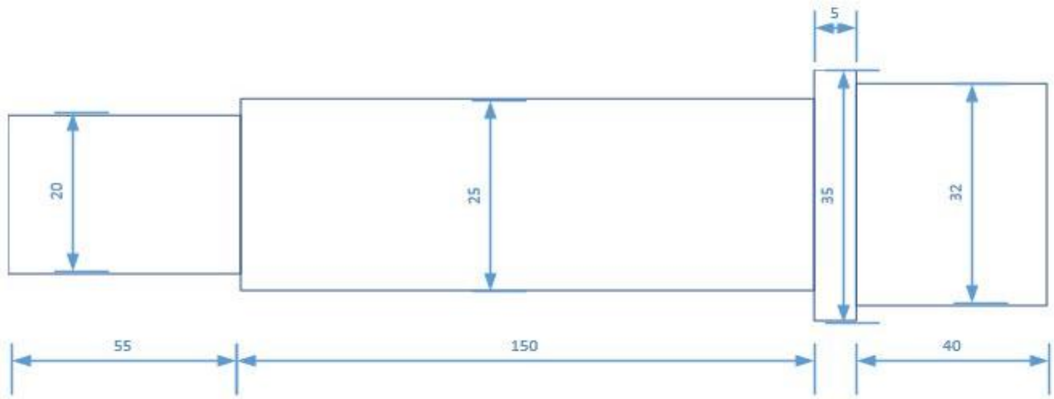


Fig. 3.2:Photograph of the developed gear box

Fig. 3.3: Rubber sealed radial ball bearing of stainless steel used to mount and support shafts holding pinion and gears.

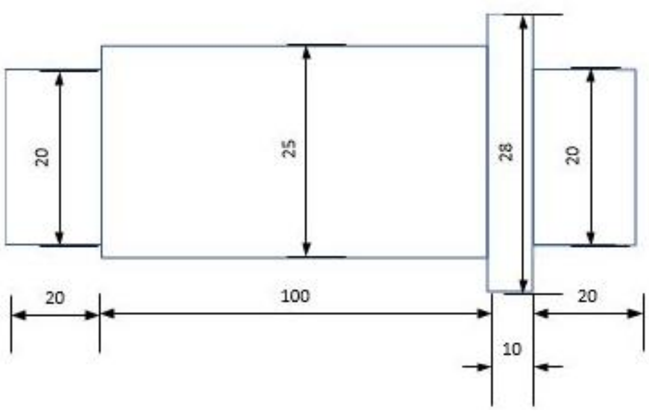
Fig. 3.4: Photograph of the bush bearing used to support workpiece gear shaft.



(a)

(b)

Fig. 3.5: (a) Drawing and (b) Photograph of shaft which was used to mount workpiece gear.



(a)

(b)

Fig. 3.6: (a) Drawing; and (b) photograph of shaft used to mount the pinion.

3.2.2 Supporting Structure

The gear box and AC motor were supported on a table of size2' x 3'and having plywood of 18 mm thick as its top as shown Fig. 3.7.

Fig. 3.7: Photograph of the supporting table for gear box and motor.

3.2.3 Noise and Vibration Analyzer

Noise and vibration analyzer from OROS Inc. France and its software (NV Gate, 9.0, 3-series Analyzers software) were used for measuring noise and vibrations of the running straight bevel gear and pinion. This analyzer has:8 channels data acquisition system as shown in Fig 3.8a. Accelerometer (model- 3214A2, sensitivity-97.86 mV/g) as shown in Fig. 3.8b; and condenser microphone (type- MK 250; NO.:12791; sensitivity- 42.9 mV/Pa) BNC cable was used to connect the microphone and accelerometer to the OROS analyzer. The accelerometer was mounted on the casing of output shaft of the gear box to measure the vibrations level and the microphone were kept 1.2 meter apart from the gear box to measure the noise level.

(a)

(b)

Fig. 3.8: (a) OROS 8-channel analyzer; (b) Accelerometer; and (c) Microphone

3.2.4 Prime Mover System

One 3-phase AC motor of 1 hp power capacity, as shown in Fig. 3.9a, was used to rotate the input shaft of the gear box. Variable frequency drive from L&T (model no. CX2000) as shown in Fig. 3.9b was used to control the speed of the AC motor.

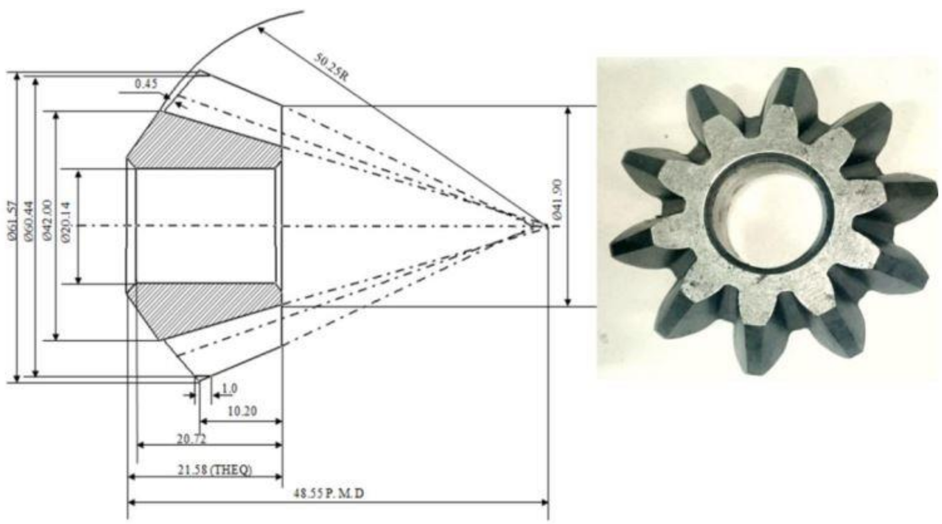
(a)

(b)

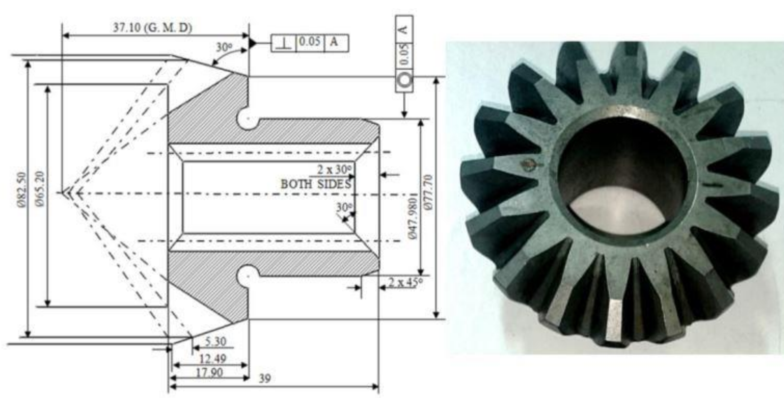
Fig. 3.9: (a) AC motor (b) Variable frequency drive to control the speed of motor.

3.3 Details of Pinion and Workpiece Gears

The pinion and workpiece gears used in the analysis were straight bevel gears having 4.83 mm module. Workpiece gear has 16 teeth while pinion has 10 teeth. The workpiece gears and pinion were made of case hardened 20MnCr5 alloy steel and having surface hardness of 50-54 and 58-62 HRC respectively. This grade of alloy steel was selected as workpiece gear material because it is the most commonly used material for the production of commercial bevel gears for typical industrial application. Figure 3.10a depicts the detailed drawing and photograph of workpiece gear and drawing and photograph of pinion (3.10b). Table 3.1 present the design parameters of pinion and workpiece gear along with their material composition, properties and selection criteria.



(a)



(b)

Fig. 3.10: (a) Drawing and photograph of pinion; (b) Drawing of workpiece gear and its photograph**.**

Table: 3.1 Design parameters of pinion and workpiece gears along with their material composition, properties and selection criteria.

Parameter		Pinion	Workpiece Gear
Design Parameters	Module	4.83	4.83
	No of teeth	10	16
	Pressure angle	22.5	22.5
	Cone angle		
	1. At Face	42.5	62.5
	2. At Pitch	32	58
	3.At root	25	49.5
	Pitch apex to crown height	38.44 mm	24.05 mm
Material		20MnCr5 with case hardening of 58-62 HRC	20MnCr5 with case hardening of 52-56 HRC
Composition		C: 0.14 -0.19; Mn: 1-1.3; P: 0.035 Max.; S: 0.035 Max.; Si: 0.15-0.4; Cr: 0.8-1.1; Fe: balance	
Properties		Mechanical properties Tensile strength: 800-1100 N/mm^2 Yield strength: 600 N/mm^2 Elongation (min): 10% Hardness (HBN): 230-320	
Selection Criteria		Industrial Application (used in the differential mechanism of Tata-407 vehicle)	

Chapter 4

Noise and Vibration Results

The noise and vibration data reported in the current work were acquired from tests of straight bevel gears test rig. The noise and vibration data were periodically collected from the gear box at different rotational speed and load.

4.1 Results of Unfinished straight bevel gear

Table: 4.1. Values of noise and vibrations for the unfinished bevel gear at different load and speed.

Load (N)	RMS value of Noise (dB)				RMS value of Vibration (mm/s^2)			
	1000 rpm	750 rpm	500 rpm	250 rpm	1000 rpm	750 rpm	500 rpm	250 rpm
60	85	80	60	51.6	398.2	404.8	386	369.8
50	82	79.4	57.6	49.7	414.3	382.6	362.4	355.8
40	80.2	74.6	55	50	396	404.7	323.1	302
30	76.3	66	51.6	45.7	388	373.4	249.3	206.8
No load	68	65	47.4	45.8	176.5	159.4	97	93

4.2 Results of Gear Finished by ECH process

Table: 4.2. Values of noise and vibrations for the best finished straight bevel gear by ECH process (**Shaikh, 2013)** at different load and speed.

Load (N)	RMS value of Noise (dB)				RMS value of Vibration (mm/s^2)			
	1000	750	500	250	1000	750	500	250
60	83	77.7	58.2	50.9	330.6	305.6	357.4	343.2
50	80	75.3	57.1	49.3	372.3	398.2	314	341.3
40	79.2	73	54.2	49	408	371	304.8	278.7
30	75.3	63	50.8	45.3	369	321.3	266.8	175.9
No load	66.5	64	46.8	44.1	165.8	143.7	83	81.3

4.3 Results of gear finished by PECH process

Table: 4.3. Values of noise and vibrations for the best finished straight bevel gear by PECH process (**Pathak, 2016**) at different load and speed.

Load (N)	RMS value of Noise (dB)				RMS value of Vibration (mm/s^2)			
	1000 rpm	750 rpm	500 rpm	250 rpm	1000 rpm	750 rpm	500 rpm	250 rpm
60	82	76.1	56.7	50.4	353.7	297.3	278.3	326.9
50	79	72.8	56	48.9	322.4	357.6	296	301.6
40	78.6	71.8	53	47.1	376	353.4	262.2	194
30	72.8	61.4	50.2	46	349	336.8	196.3	186
No load	64	62.3	46.1	43.6	151.4	134.9	79.4	75.3

Table: 4.4. Values of surface roughness, micro-geometry and overall values of noise and vibrations of straight bevel gears.

Gear Condition	**Parameters of surface roughness**		**Parameters of micro-geometry**				**Load (N)**	**RMS value of Noise (dB)**				**RMS value of Vibration (mm/s^2)**			
	Average surface roughness (R_a)	Maximum surface roughness (R_{max})	Average value of single pitch error (f_p)	Average value of adjacent pitch error (f_u)	Average value of cumulative pitch error (F_p)	Run out (F_r)		1000 rpm	750 rpm	500 rpm	250 rpm	1000 rpm	750 rpm	500 rpm	250 rpm
Unfinished	1.87	12.94	26.2	34.3	64.8	34.4	60	85	80	60	51.6	398.2	404.8	386	369.8
							50	82	79.4	57.6	49.7	414.3	382.6	362.4	355.8
							40	80.2	74.6	55	50	396	404.7	323.1	302
							30	76.3	66	51.6	45.7	388	373.4	249.3	206.8
							No load	68	65	47.4	45.8	176.5	159.4	97	93
Best finished gear by ECH **(Shaikh, 2013)**	1.31	9.82	23.2	16.6	54.3	25.4	60	84	77.7	58.2	50.9	330.6	305.6	357.4	343.2
							50	80	75.3	57.1	49.3	372.3	398.2	314	341.3
							40	79.2	73	54.2	49	408	371	304.8	278.7
							30	75.3	63	50.8	45.3	369	321.3	266.8	175.9
							No load	66.5	64	46.8	44.1	165.8	143.7	83	81.3
Best finished gear by PECH **(Pathak, 2016)**	1.02	5.96	19.9	23.4	49.5	23.4	60	82	76.1	56.7	50.4	353.7	297.3	278.3	326.9
							50	79	72.8	56	48.9	322.4	357.6	296	301.6
							40	78.6	71.8	53	47.1	376	353.4	262.2	194
							30	72.8	61.4	50.2	46	349	336.8	196.3	186
							No load	64	62.3	46.1	**43.6**	151.4	134.9	79.4	**75.3**

Table 4.4 presents the results of overall noise and vibrations values of straight bevel gears. On the basis of these results it has been seen that gears of better quality have low level of noise and vibration. It is also observed that when the rpm of gear box increased then the level of noise and vibration also increase by some notable magnitude. As we have seen that gears of PECH finished have good quality of surface roughness and micro-geometry. From the table 4.3 PECH finished straight bevel gear have low level of noise and vibration as compared to ECH finished straight bevel gears and unfinished bevel gear.

It has also been observed that ECH finished straight bevel gear have low level of noise and vibration as compared to unfinished bevel gear. As ECH finished straight bevel gears have better surface roughness values and values of micro-geometry compared to unfinished bevel gears. So, from the previous discussion we can say that better quality of gears will give low level of noise and vibrations.

4.4 Analyses of Results

4.4.1 Noise Level Analyses of Straight Bevel Gears.

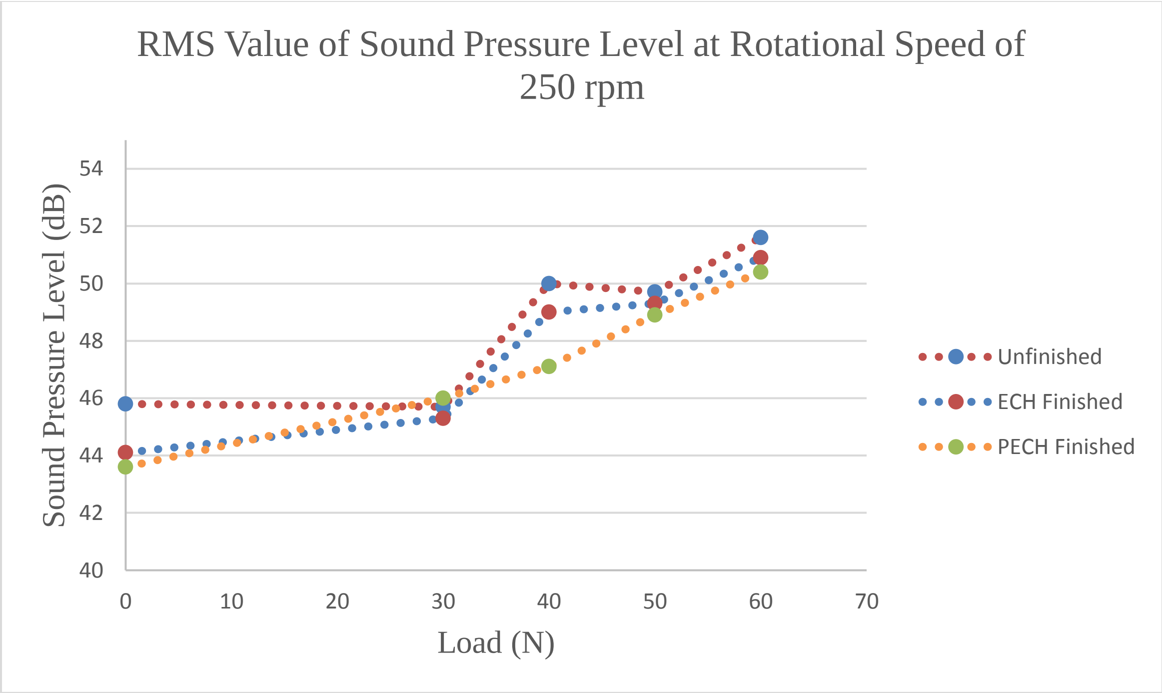


Fig. 4.3 Sound pressure level of straight bevel gears at rotational speed of 250 rpm

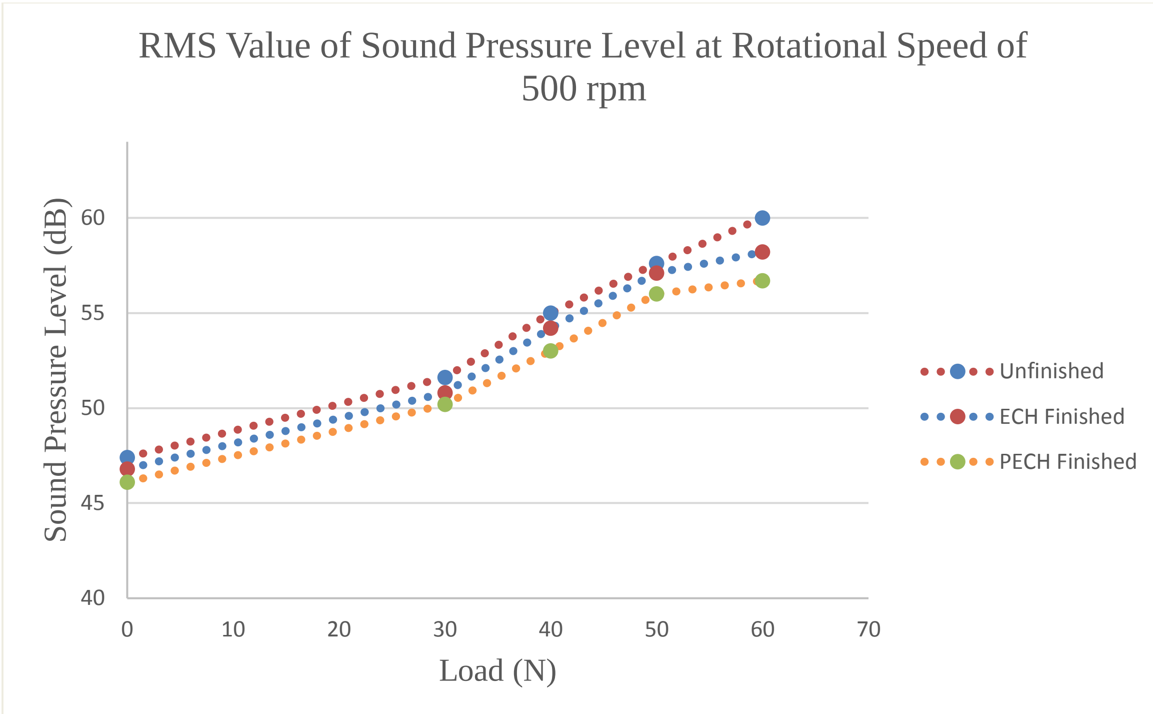


Fig. 4.1 Sound pressure level of straight bevel gears at rotational speed of 500 rpm

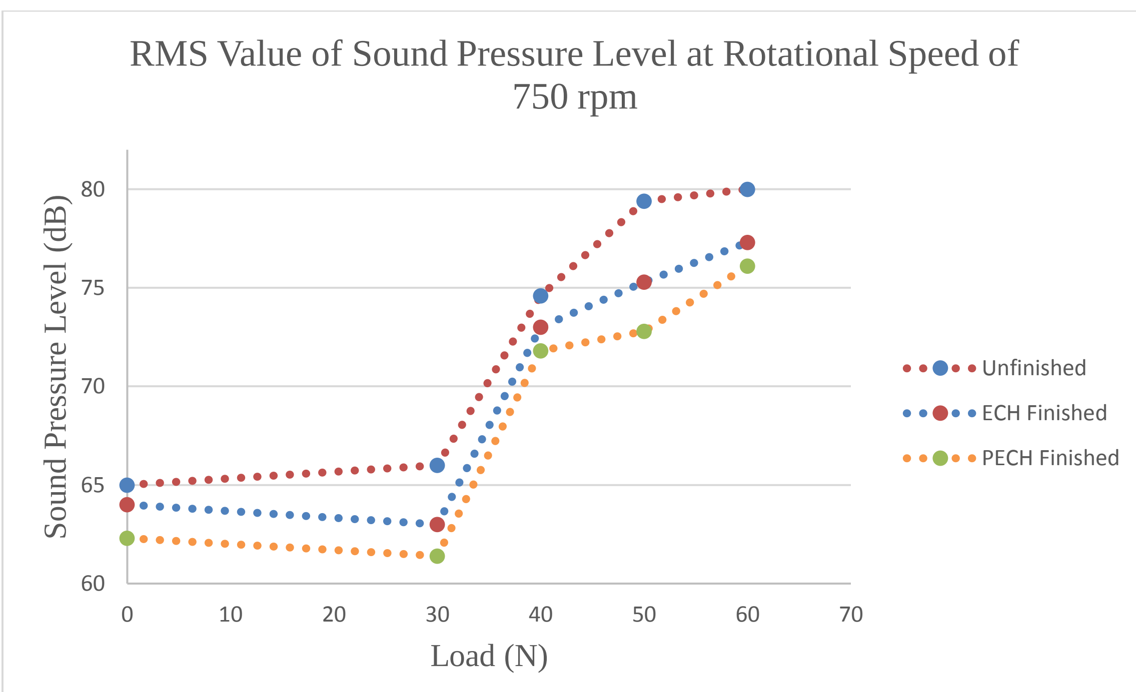


Fig. 4.2 Sound pressure level of straight bevel gears at rotational speed of 750 rpm

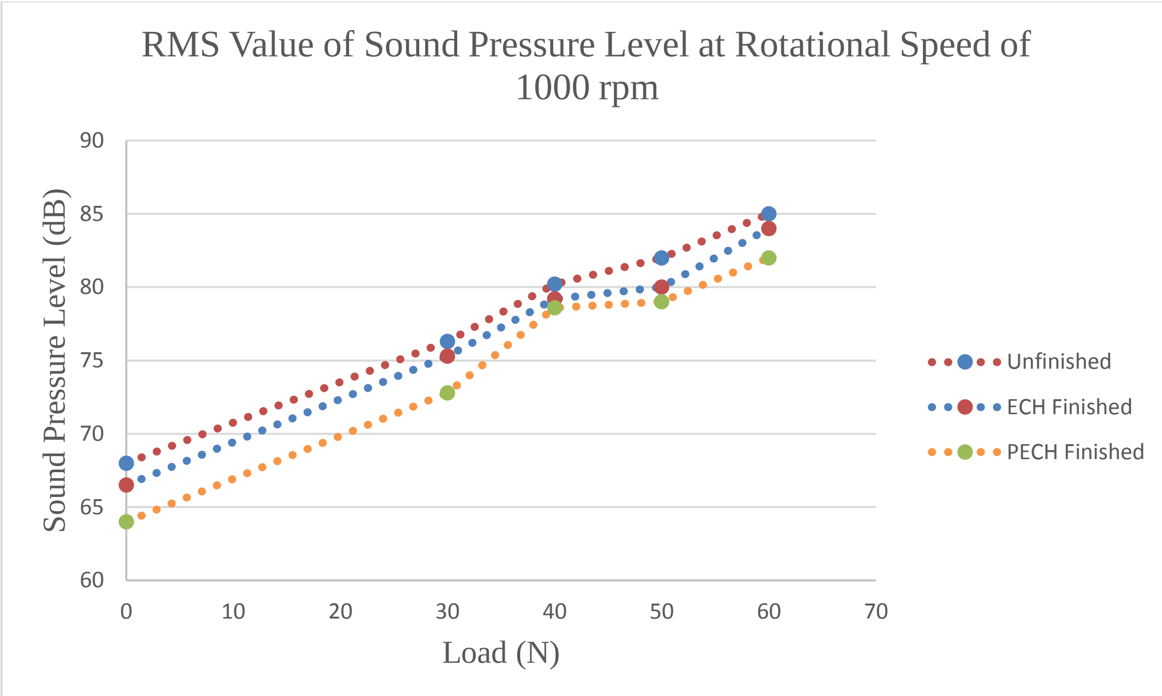


Fig. 4.4 Sound pressure level of straight bevel gears at rotational speed of 250 rpm

4.4.2 Vibrations Level Analyses of straight bevel gears

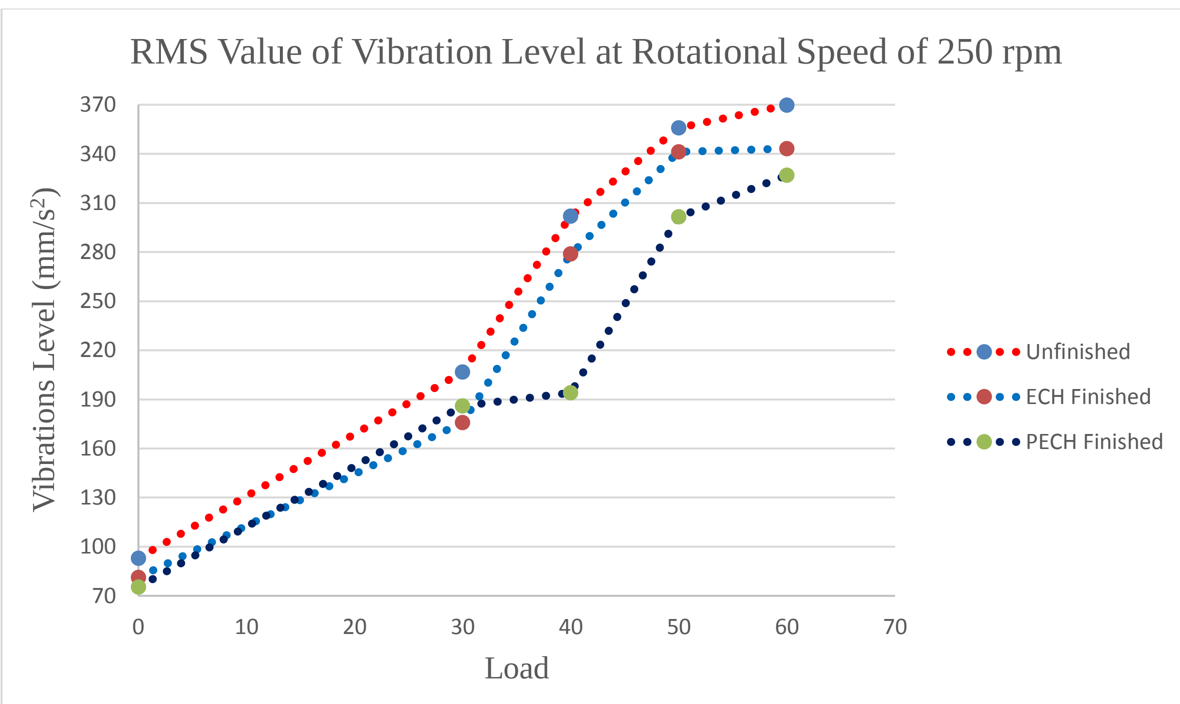


Fig. 4.5 Vibration level of straight bevel gears at rotational speed of 250 rpm

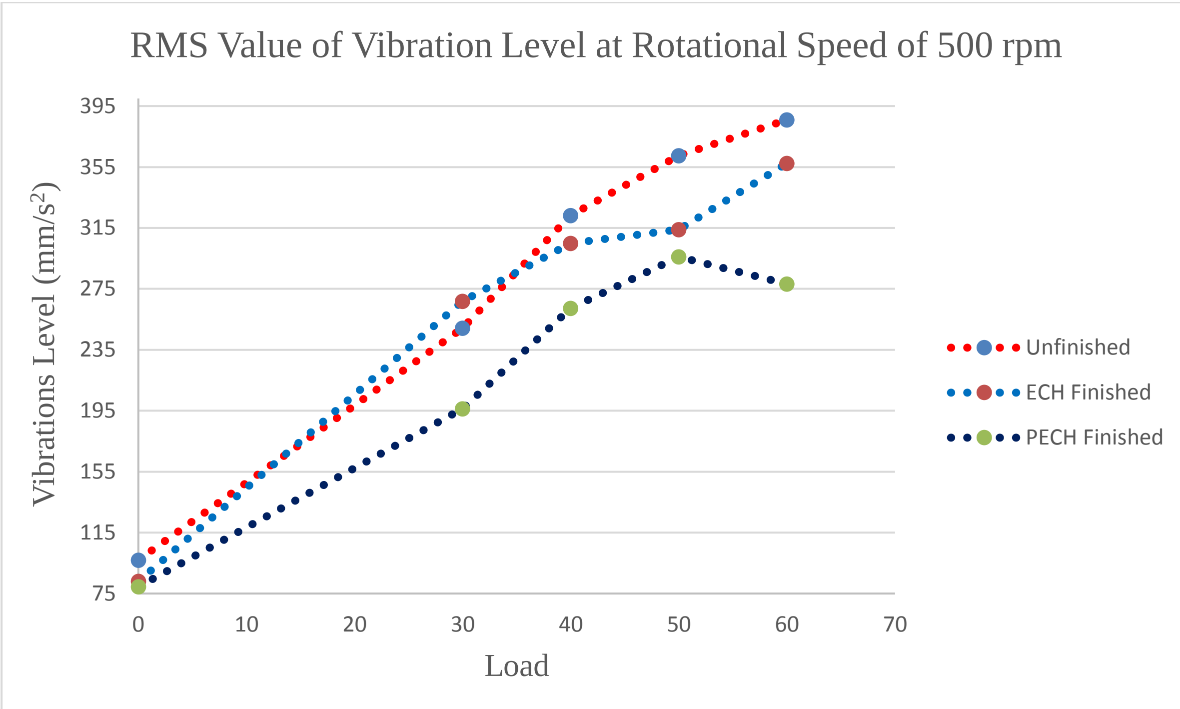


Fig. 4.6 Vibration level of straight bevel gears at rotational speed of 500 rpm

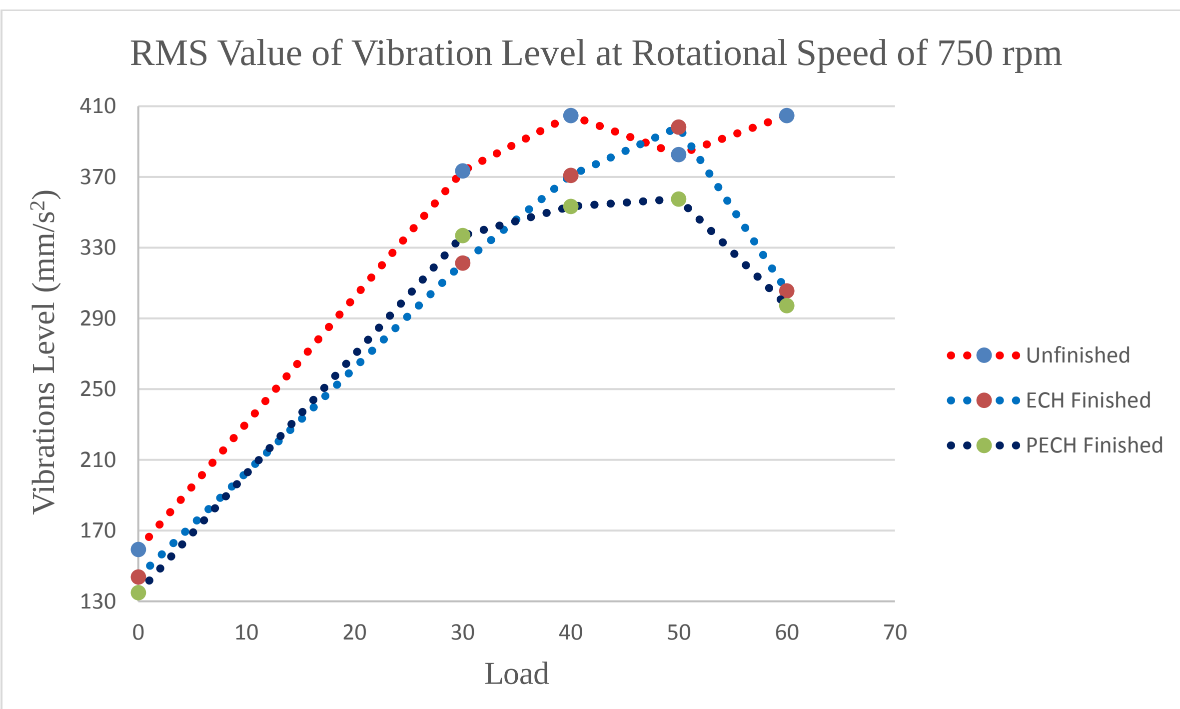


Fig. 4.7 Vibration level of straight bevel gears at rotational speed of 750 rpm

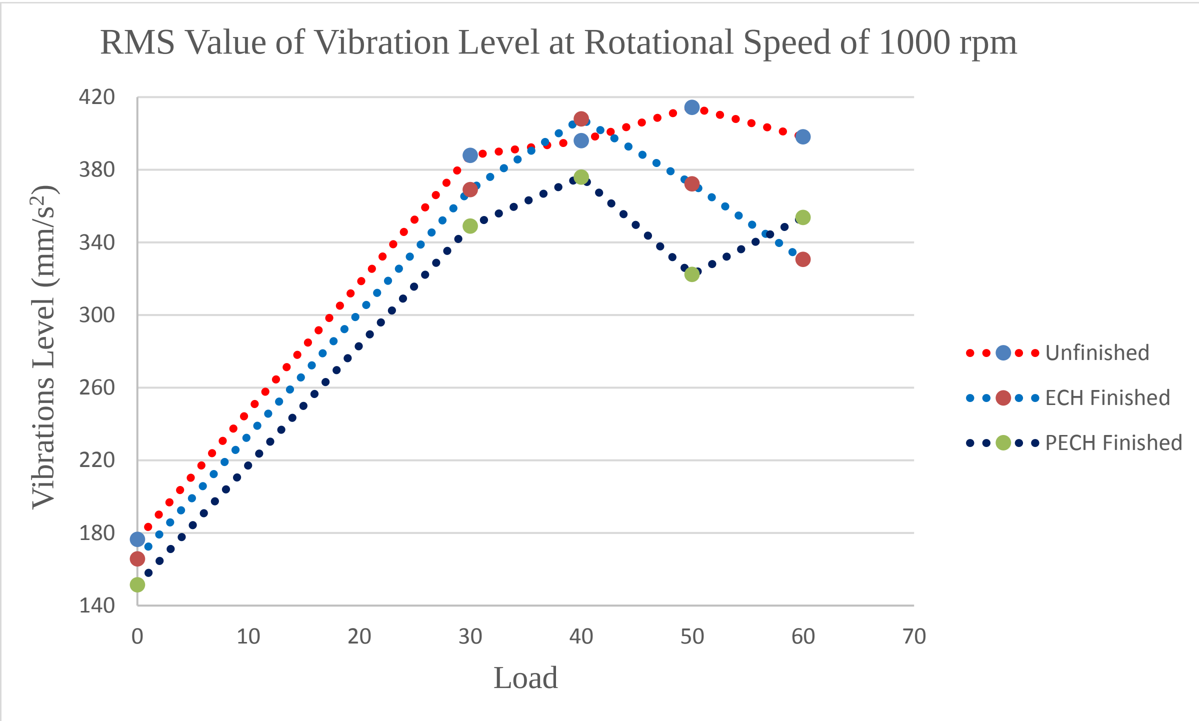


Fig. 4.8 Vibration level of straight bevel gears at rotational speed of 1000 rpm

Chapter 5

Conclusion and Scope for the Future Work

This chapter presents the conclusions from the present work and scope for the future work.

5.1 conclusions

Following conclusions can be summarized from the present research work:

1. The analysis of the results found better quality of gears have low level of noise and vibrations. As gears finished by PECH process have better quality than gears finished by ECH process and unfinished gears.
2. Quality of unfinished gear have DIN standard 9 for single pitch error; DIN standard 10 for adjacent pitch error and DIN standard 9 for runout.
3. Quality of gears finished by ECH process have DIN standard 7 for single pitch error; DIN standard 8 for adjacent pitch error and DIN standard 8 for runout.
4. Quality of gears finished by PECH process have DIN standard 8 for single pitch error; DIN standard 6 for adjacent pitch deviation and DIN standard 7 for runout.
5. Surface roughness of unfinished gear have 1.87 µm for average surface roughness; and 12.94 µm for maximum surface roughness.
6. Surface roughness of gear finished by ECH process have 2.0 µm for average surface roughness; and 8.8 µm for maximum surface roughness.
7. Surface roughness of gear finished by PECH process have 1.06 µm for average surface roughness; and 6.90 µm for maximum surface roughness.
8. It can be concluded that unfinished bevel gear has high level of noise and vibration values than gear finished by ECH and PECH process because of its gear quality.

5.2 Scope for the Future Work

Since the present work was very first attempt to establish the relation of finishing of gears and noise of gears during meshing. In this research only two advanced finishing processes is compared with unfinished bevel gears therefore there is lot of scope for future work in this area. Some of the directions for future work are as follows:

- Compare all the unconventional finishing processes for bevel gears with unfinished bevel gears at the level of noise and vibrations.

- Compare all the advanced finishing processes of bevel gears with unfinished bevel gears for noise and vibrations.
- Compare unconventional bevel gears finishing processes with advanced bevel gears finishing processes for noise and vibrations.
- Make a relation between quality of gears and level of noise and vibrations.
- Make a relation between micro-geometry and surface roughness of bevel gears with the level of noise and vibrations, and find out the most critical parameters which affect the noise and vibrations level.

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