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Design, Manufacturing and Vibration Analysis of Defects in Spur Gear Box

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Abstract: *Gears are important element in a variety of industrial applications such as machine tool and gearboxes. An unexpected failure of the gear may cause significant economic losses. For that reason, fault diagnosis in gears has been the subject of intensive research. Vibration signal analysis has been widely used in the fault detection of rotation machinery. The vibration signal of a gearbox carries the signature of the fault in the gears, and early fault detection of the gearbox is possible by analysing the vibration signal using different signal processing techniques. In this dissertation vibration analysis of spur gear box is done by FEA and experimental method. Design of spur gear box is done on basis of given working parameters using SI units and design data book and same design parameters are used for fabrication. During initial phase of project process capability analysis is done on existing gear box. Further analysis is done by inducing defects such as decrease in height of gear tooth and crack at tooth base. Their performances were checked on basis of noise analysis. An attempt is made to decrease the stresses in gear tooth by inducing cavities of various shapes at various locations using FEA. The performance of gear box is tested at 0kg, 3kg, 6kg, 9kg and speed for 1400 rpm. Frequency measurement at working loading condition is performed using FFT analyser. Natural frequencies at different loading condition are determined by using FFT analyser. The experimental results obtained by above testing are validated with finite element analysis and the results found satisfactory and within the range.*

Keywords: Vibration, Fault Diagnosis, Condition Monitoring, Gearbox, etc.

I. INTRODUCTION

1.1 Problem Definition

The undergoing Project Company, "Vedant Enterprises" Pune, manufactures gears & gear box as per customer's requirement. As per one of the demands of design and manufacturing of Spur & Spur gear box for 0.5HP motor, Company needs to set such a system which should check the vibration occurs in the gearbox, easy to understand for operators, should be as efficient as, and meeting with the quality aspects with improved in design. Therefore, for vibration analysis FEA and FFT are used.

1.2 Objective

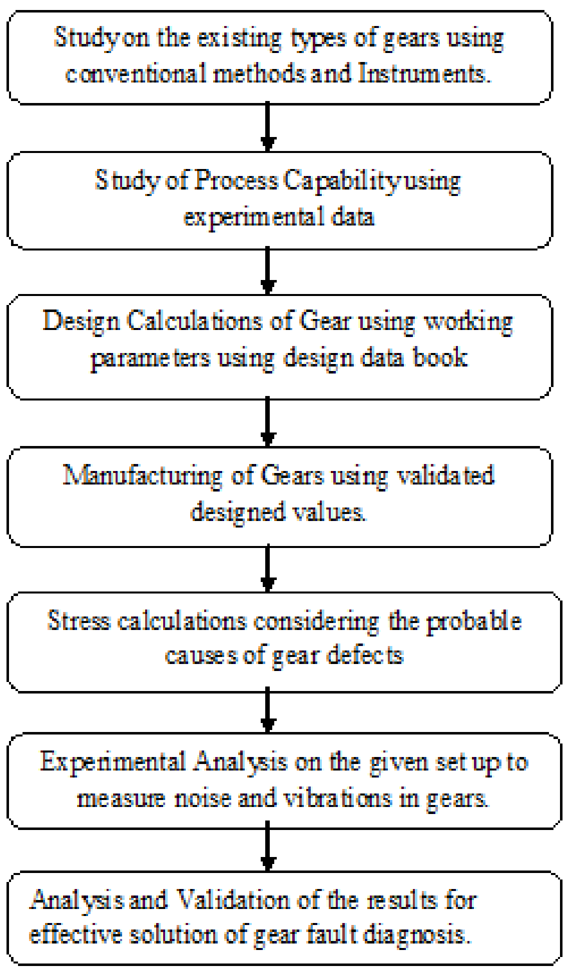
1. Inspection of Various types of gears using various metrological instruments like gear tooth vernier caliper (0-150 mm range and least count of 0.2).
2. Calculations of various inspection parameters by considering spur gear using cause and effect diagram, to calculate its process capability.
3. Design and manufacturing of spur gear with given working parameters and finalizing the safe values of gear parameters using various design equations.
4. To evaluate the performance of gear box by inducing various defects at various loading conditions using noise meter.

5. FEA analysis of various possible causes of gear tooth failure and validating the same with results obtained by experimental analysis.
6. FFT analysis at various loading condition for Noise and vibration detection and natural frequencies calculations of possible defects in spur gears to identify the problems in gear at design stages and to find out the remedial measures.

1.3 Scope

Gears are important element in a variety of industrial applications such as machine tool and gearboxes. An unexpected failure of the gear may cause significant economic losses. For that reason, fault diagnosis in gears has been the subject of intensive research. Vibration signal analysis has been widely used in the fault detection of rotation machinery. The vibration signal of a gearbox carries the signature of the fault in the gears, and early fault detection of the gearbox is possible by analysing the vibration signal using different signal processing techniques. This vibration monitoring technique can be applied to detect Backlash, Scoring, and Pitting of the gear teeth.

1.4 Methodology



II. LITERATURE SURVEY

Table 1: Summary of Literatures

Name of Author	Title of Paper and Year of Publication	Work Completed	Scope for further work
G. S. Lamani, et.al.	Vibration analysis of worm and worm wheel gear box (2018)	Vibration analysis in frequency spectrum for worm gear	Similar work for other types of gear
Ganesh Survase, et.al.	Study & Vibration analysis of worm and worm wheel gear box by using FFT Analyzer (2018).	Vibration analysis techniques used for condition monitoring in gear fault.	Similar work for other types of gear
P. Jagadesh, et.al.	Design and analysis of a Gear Box Motor Current (2017)	Defects in gears of a multistage automotive transmission gearbox at different gear operations using MCSA as a condition monitoring technique.	FEA Analysis for design modification
Miss. Radhika Laxman Patil et.al.	A Review Paper on Design, Optimization and Testing of Special Purpose Worm and Worm Wheel Gearbox for Butterfly Valve Operation (2017)	Higher standard output torque gearboxes which are uneconomical, heavy as well as large in size.	Similar work for other types of gear
Rishav Ranjan, et.al.	Harmonic Response Analysis of Gearbox (2017)	Stress and the safe operating frequencies for different materials to avoid resonance.	FEA and design modifications

Summarization of Literature Survey

1. Very few works have done so far for spur and types of gear boxes.
2. FFT Analysis can be used for further modified frequency analysis.
3. Metrological aspects can be considered to reduce defects using various quality control tools and techniques.
4. Design modification can be done by considering strength analysis inducing minute holes on gear at various location with different shapes and sizes at area with less stress concentration.
5. FEA analysis can be performed for the aforesaid criteria.
6. Gear tooth noise study can be used by inducing different defects like decrease in height of tooth and crack initiation at root.
7. Overall, a simplest way can be proposed for shop floor workers to immediately identification of gear tooth by its noise and vibrations.

III. DESIGN AND THEORETICAL ANALYSIS

Table 2: Material Properties for gear

Table 2: Material properties of pinion (Cast Steel) ASTM				**Chemical Requirements**		**Tensile Requirements**			
Steel Grade	C	Mn	Si	S	P	Tensile Strength	Yield Point	Elongation in 2 in.	Reduction of Area
Max % / Range				Min. ksi [Mpa] /			Min. %		
ASTM A27 / A27M									
ASTM A27, Grade 65-35	0.30	0.70	0.80	0.06	0.05	65 [450]	35 [240]	24	35

Following readings were taken for tooth thickness of one of the gears with tooth specification 7.8 a study of 50 consecutive pieces shows the following measurement put into 10 groups of 5 each, 0.05mm.

Table 3: Spur gear tooth width of given specimens.

1	2	3	4	5	6	7	8	9	10
7.71	7.68	7.68	7.62	7.68	7.62	7.62	7.68	7.62	7.77
7.68	7.68	7.71	7.77	7.69	7.71	7.71	7.62	7.68	7.62
7.77	7.62	7.62	7.71	7.71	7.68	7.68	7.71	7.62	7.74
7.62	7.77	7.72	7.68	7.77	7.73	7.77	7.77	7.71	7.68
7.70	7.71	7.75	7.77	7.75	7.70	7.69	7.78	7.72	7.71

Process capability found to be 2.476354. Specification limits are, 7.8 ±0.05mm. i.e., 7.85 mm and 7.75mm obviously the process capability being more than tolerance value, rejection will be there. Percent defective = 34.318 %(approximately). It is found that, rejection is much more and it does not meet the specification limits. This can be reduced by changing the machine setting to 7.8 mm. Further quality improvement techniques like check sheet, control charts, Pareto charts etc. can be implemented for inline inspection are proposed.

Design Calculations:

Working Parameters:

1. Running speed of machine: 300 rev/min.
2. Motor specification: 15 KW and 1200rev/min
3. Gear specification: 14.50full depth
4. Center distance: 0.375 m
5. Material of pinion: C30 forged, hardened and tempered steel
6. Material of gear: cast steel
7. Assumption: Medium shock condition.

Table 4: Designed values for manufacturing and analysis

Sr. No.	Parameter	Abbreviation	Designed Value
1	Diameter of Pinion	Dp	150mm
2	Diameter of Gear	Dg	600mm
3	Module	m	5mm
4	Number of teeth on pinion	zp	30
5	Number of teeth on gear	zg	120
6	Diameter of Addendum Circle for Pinion	Dap	160mm
7	Diameter of Dedendum Circle for Pinion	Ddp	137.5mm
8	Diameter of Addendum Circle for gear	Dag	610mm
9	Diameter of Dedendum Circle for gear	Dag	587.5mm
10	Web thickness (Pinion)	wt	9mm
11	Rim thickness (Pinion)	rt	8mm
12	Hub Diameter (Pinion)	Hdp	66mm

13	Hub Length (Pinion)	Hlg	50mm
14	Major axis at rim end (gear)	b	20.5mm
15	Minor axis at rim end(gear)	a	10.25mm
16	Depth of circumferential rib	h	11mm
17	Thickness of rib	w	10mm
18	Diameter of Shaft	d	50mm
19	Hub Diameter(gear)	Hdg	90mm
20	Hub Length(gear)	Hlg	62.5mm

Figure 1: Experimental test rig

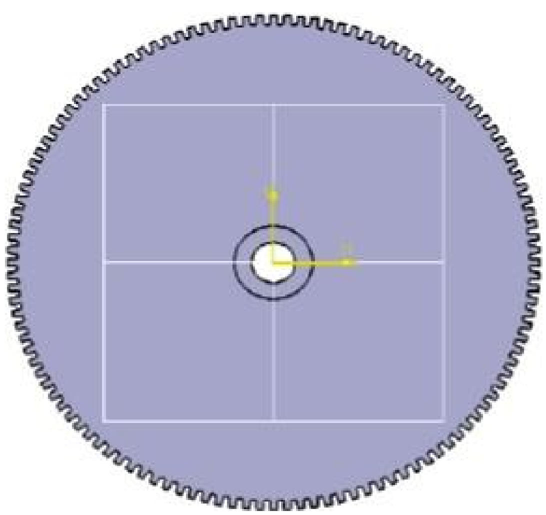


Figure 2: Gear: 120 teeth made up of cast steel

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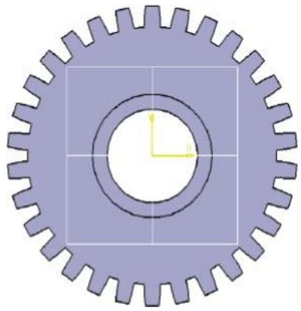

Figure 3: Pinion 30 teeth made up of C30 forged, hardened and tempered steel.

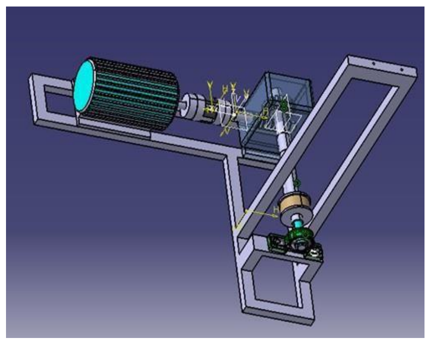

Figure 4: CAD model of assembly

IV. TESTING AND EXPERIMENTATION

For the experimental and diagnostic analysis following cases are studied,

1. Artificial defects have been produced in the healthy output gear. With the help of wire EDM three different dimensions of cut have been produced at the root of one tooth which develops stress concentration which propagates crack.
2. Three different types of cracks were produced with the help of wire EDM and the same were measured using profile projector as listed below.
3. Similar experimentation was performed by considering decrease in gear tooth.
4. Noise measuring study is performed for all cases to check variation in noise as per changes in vibrations.
5. FEA analysis Stress and Reduction of a Spur gear by adding different shaped holes to reduce stress concentration.
6. FFT Analysis is performed for vibration analysis at different frequencies.

Table 6: Induced Defects in Gear leading to noise and vibrations

Crack (Gear) Length of crack along the face width of tooth			
	Case 1	Case 2	Case 3
Height	0.322mm	0.322mm	0.322mm
width	1.575 mm	2.745 mm	3.365 mm
Reduction in Tooth Height (Gear)			
Case 1		Case 2	Case 3
Percentage reduction in tooth height	40%	75%	100%

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Results and Discussion of induced tooth defects

There were two artificial defects imposed in the gear to study the gear box noise for fault analysis. Experiments were conducted with healthy gear, faulty gear with different crack C1, C2, C3, decrease in tooth height by 40%, 75% and 100%, each at test gear speed 180, 360, 540, 725 and 900 rpm respectively. For both case results are discussed below,

CASE-I [CRACK]

Normal Gear

Table 7: Peak sound pressure level in dB (A) vs. speed with crack

Motor Speed (Input)	500 RPM	1000 RPM	1500 RPM	2000 RPM	2500 RPM
Test Gear Speed (Output)	180 RPM	360 RPM	540 RPM	725 RPM	900 RPM
Normal Gear	59.1	62.9	68.3	72.0	74.7
Crack (Case 1)	63.2	66.6	71.0	74.7	77.7
Percentage increase in (Case 1)	6.93%	5.58%	3.95%	3.75%	4.01%
Crack (Case 2)	64.4	68.6	72.7	76.7	80.8
Percentage increase in (Case 2)	8.69%	9.06%	6.44%	6.52%	8.16%
Crack (Case 3)	65.4	69.5	73.5	78.4	82.1
Percentage increase in (Case 3)	10.65%	10.49%	7.61%	8.88%	9.90%

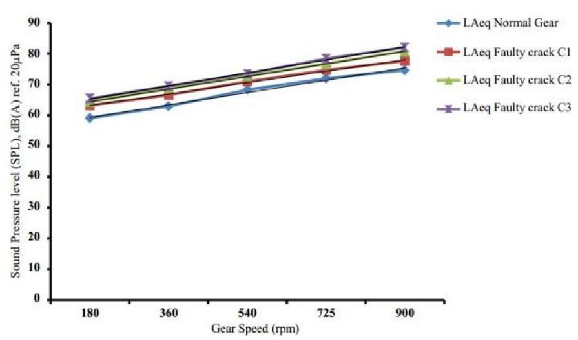

Figure 5: Sound pressure level vs. Speed with cracks for case-I crack

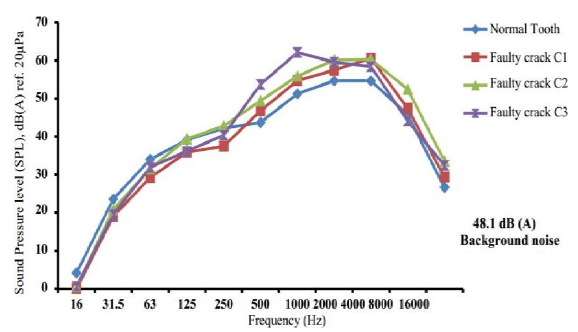

Figure 6: Sound pressure level vs. Frequency at 180 RPM

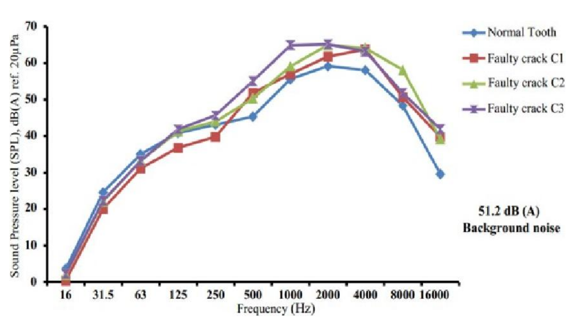

Figure 7: Sound pressure level vs. Frequency at 360 RPM

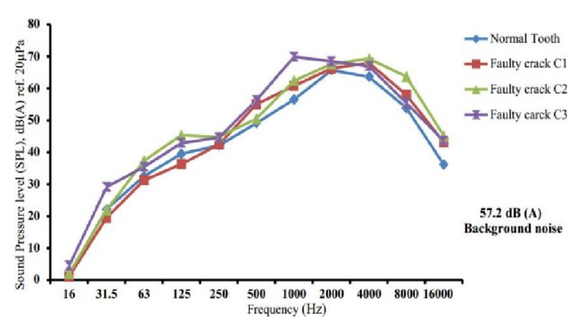

Figure 8: Sound pressure level vs. Frequency at 540 RPM

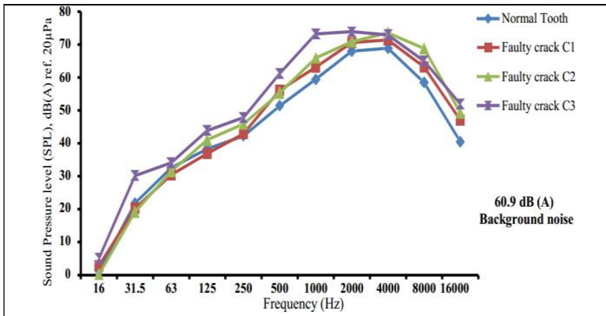

Figure 9: Sound pressure level vs. Frequency at 725 RPM

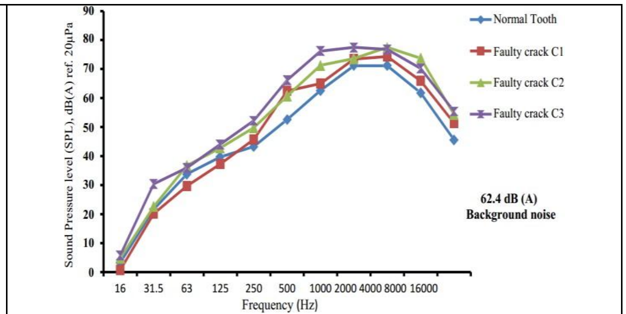

Figure 10: Sound pressure level vs. Frequency at 900 RPM

Table 8: Peak sound pressure level at frequencies w.r.t. speed

Test Gear Speed		180 RPM	360 RPM	540 RPM	725 RPM	900 RPM
Normal Gear	1KHz					
	2KHz	54.7dB(A)	59.1 dB(A)	65.7 dB(A)		71.2 dB(A)
	4KHz	54.7dB(A)	59.1 dB(A)		68.9 dB(A)	71.2 dB(A)
Faulty crack	1KHz					
	2KHz					
	4KHz	60.6 dB(A)	63.7 dB(A)	68.0 dB(A)	71.4 dB(A)	74.4 dB(A)
Faulty crack	1KHz					
	2KHz	60.6 dB(A)	64.9 dB(A)			
	4KHz	60.6 dB(A)		69.3 dB(A)	73.6 dB(A)	77.5 dB(A)
Faulty crack	1KHz	62.1 dB(A)	65.1 dB(A)	69.9 dB(A)		
	2KHz		65.1 dB(A)		73.9 dB(A)	77.5 dB(A)
	4KHz					

CASE-II [DECREASE IN TOOTH HEIGHT]

As speed and fault increases it is seen that peak sound level increases. They range is as shown below.

Table 9: Peak sound level vs. speed with decrease in tooth height

Motor Speed (Input)	500 RPM	1000 RPM	1500 RPM	2000 RPM	2500 RPM
Test Gear Speed (Output)	180 RPM	360 RPM	540 RPM	725 RPM	900 RPM
Normal Gear	59.1	62.9	68.3	72.0	74.7
Crack (Case 1)	63.2	66.6	71.0	74.7	77.7
Percentage increase in (Case 1)	6.93%	5.58%	3.95%	3.75%	4.01%
Crack (Case 2)	64.4	68.6	72.7	76.7	80.8
Percentage increase in (Case 2)	8.69%	9.06%	6.44%	6.52%	8.16%
Crack (Case 3)	65.4	69.5	73.5	78.4	82.1
Percentage increase in (Case 3)	10.65%	10.49%	7.61%	8.88%	9.90%

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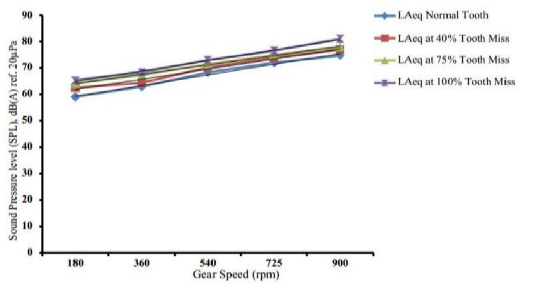

Figure 11: Sound pressure level vs. speed with decrease in tooth height

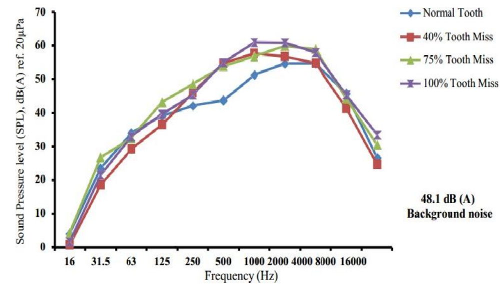

Figure 12: Sound pressure level vs. Frequency at 180 rpm

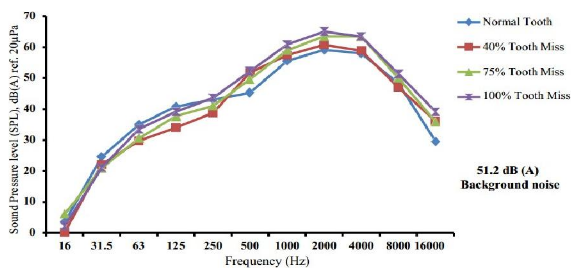

Figure 13: Sound pressure level vs. Frequency at 360 rpm

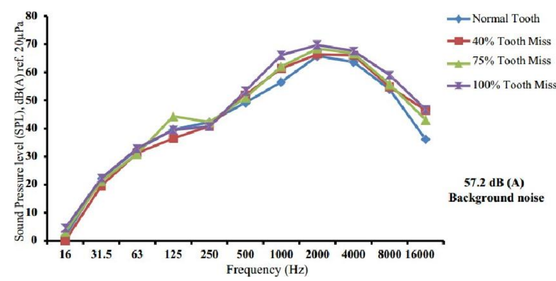

Figure 14: Sound pressure level vs. Frequency at 540 rpm

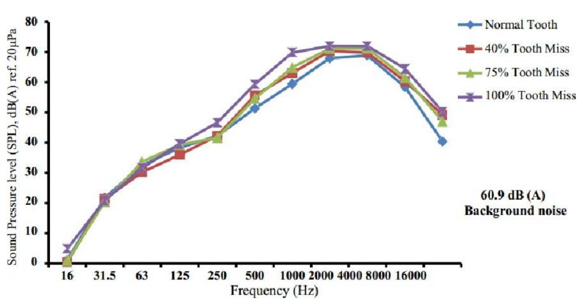

Figure 15: Sound pressure level vs. Frequency at 725 rpm

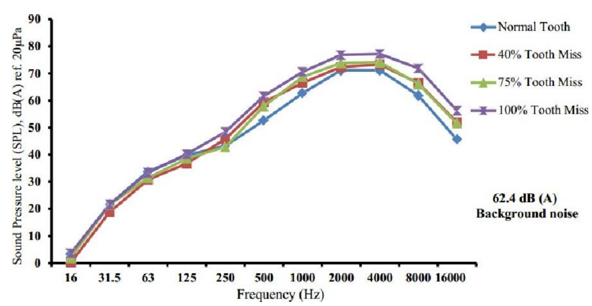

Figure 16: Sound pressure level vs. Frequency at 900 rpm

FFT Analysis

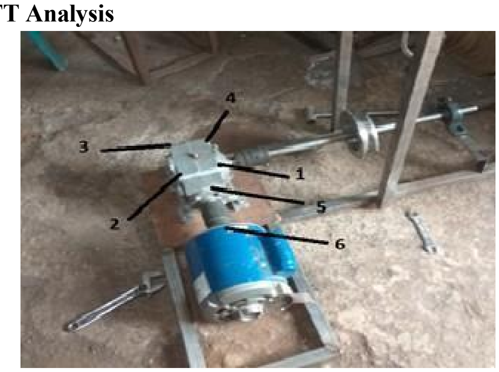

Figure 17: Node description

Figure 18: Experimental set up

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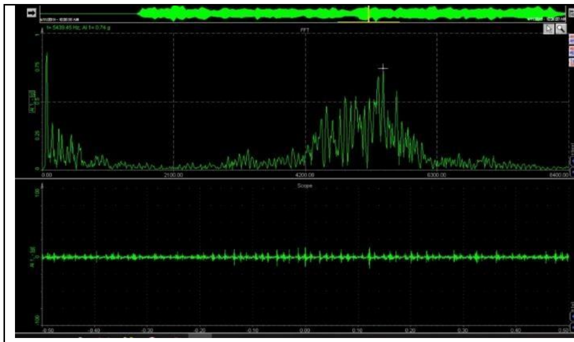

Figure 19: 0 kg axial load

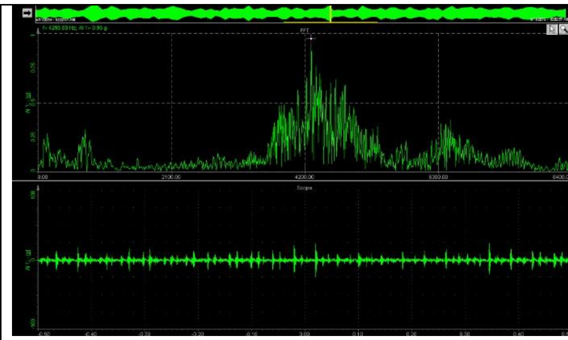

Figure 20: 0 kg horizontal load

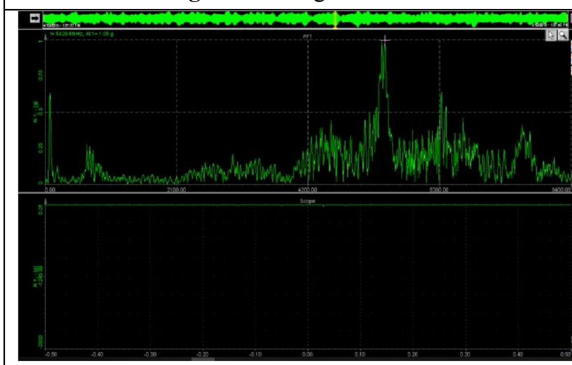

Figure 21: 0 kg vertical load

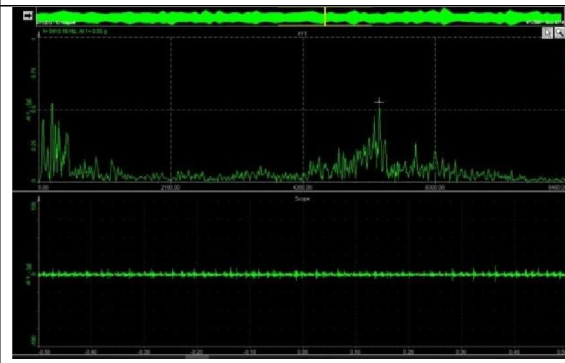

Figure 22: 3 kg axial load

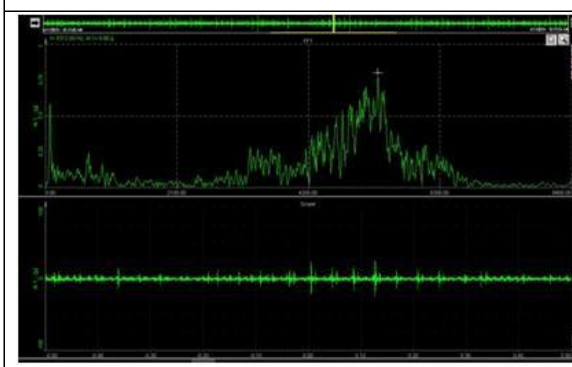

Figure 23: 3 kg horizontal load

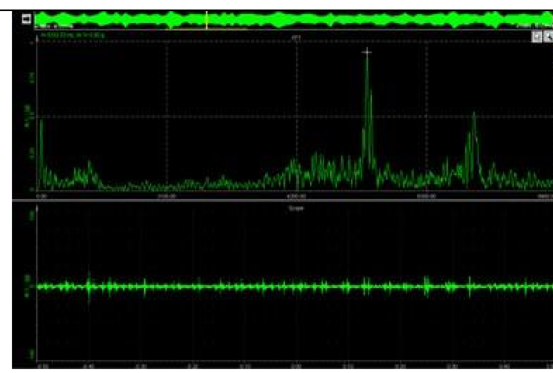

Figure 24: 3 kg vertical load

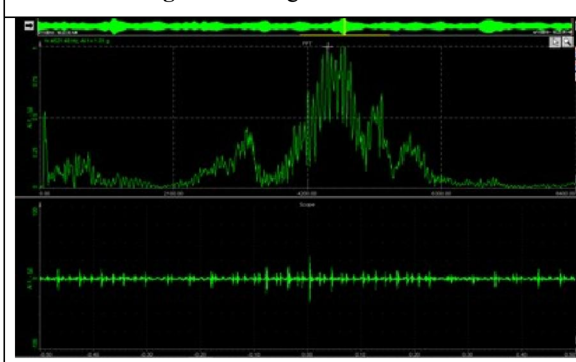

Figure 25: 6 kg axial load

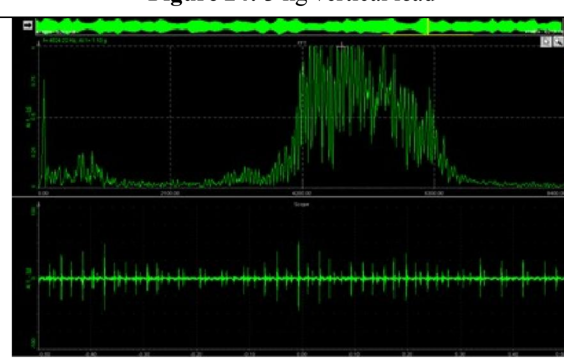

Figure 26: 6 kg horizontal load

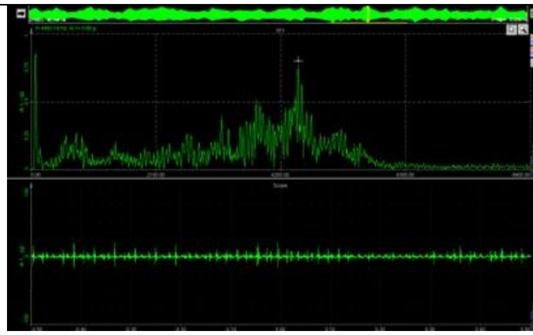

Figure 27: 6 kg vertical load

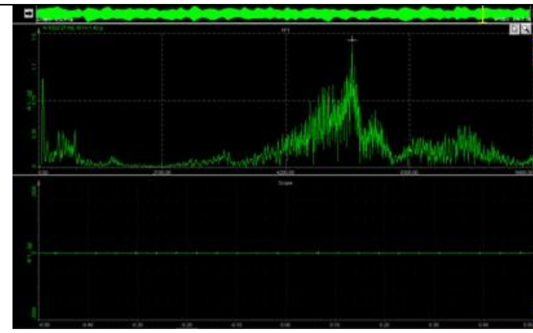

Figure 28: 9 kg axial load

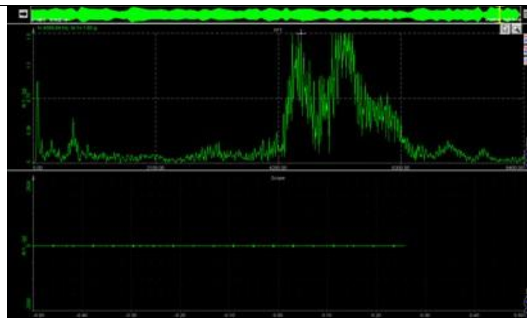

Figure 29: 9 kg horizontal load

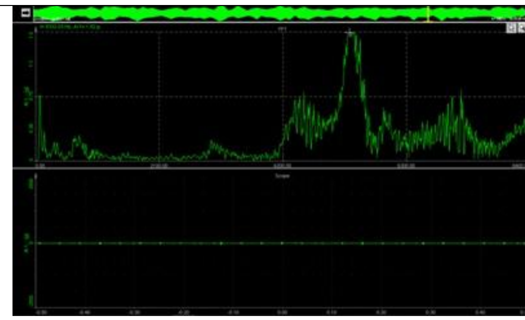

Figure 30: 9 kg vertical load

Result Summery

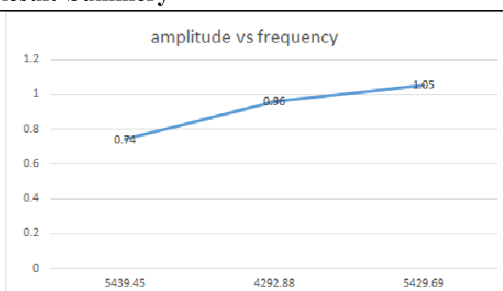

Figure 31: Amplitude vs Frequency graph for 0 kg load

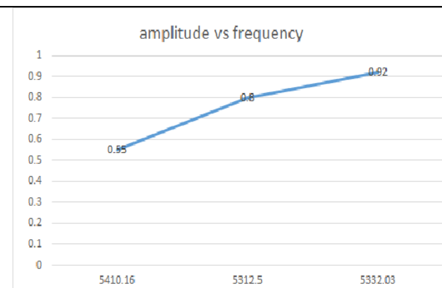

Figure 32: Amplitude vs Frequency graph for 3 kg load

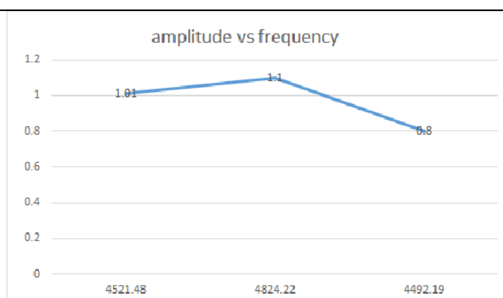

Figure 33: Amplitude vs Frequency graph for 6 kg load

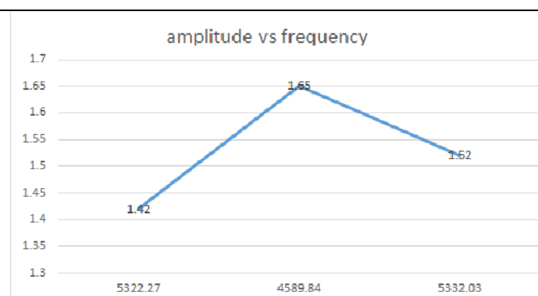

Figure 34: Frequency vs Amplitude For 9 Kg Load

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Node 1:

1. Axial: As load increase acceleration decrease with increase in frequency range.
2. Horizontal: As load increase there is decrease in peak frequency range and acceleration increase initially and then again start decreasing.
3. Vertical: As load increase there is mixed behavior of variation in acceleration and frequency.

Node 2:

1. Axial: As load increase there is decrease in frequency range but acceleration initially increases to its peak.
2. Horizontal: With increase in load frequency decrease to its minimum and then increase and same is observed to acceleration.
3. Vertical: As load increase there is increases in frequency to its minimum and then increasing with decrease in acceleration initially and then decreasing.

Node 3:

1. Axial:As Load increases acceleration decreases and then increases with same behavior of frequency.
2. Horizontal: As load increases there is decrease in acceleration with decrease in frequency.
3. Vertical: As load decrease acceleration increase with initial decrease in frequency and then increase in it.

Node 4:

1. Axial: As load increase acceleration decrease with decrease in frequency range.
2. Horizontal: As load increase there is mixed behavior of variation in acceleration and frequency.
3. Vertical: As load increase there is decrease in acceleration with initial decrement in frequency.

V. CONCLUSIONS AND FUTURE SCOPE

Conclusions:

1. Design calculations were safe as per the design criteria on basis of working parameters.
2. Process capability analysis and Fishbone diagram (Cause and effect analysis) shows the manufacturing methods are acceptable and errors are within control limits.
3. Fault of gear box are identified by measuring the gear box noise in sound pressure level. The peak noise level at mid frequencies shows that, as the crack depth increases the sound pressure level increases. Using this method and observing the graphs obtained after the study forecast of defects can be done.
4. As the height of tooth of gear decrease the sound pressure level increases. Sound pressure level also increases as the speed of gear increase.
5. Very less reduction in stress is possible with single circular hole as a stress relieving feature. Two circular holes as a stress relieving feature give more reduction than single circular hole. There is no reduction in the stress for a combination of a circular & elliptical hole.
6. Stress relieving feature having a shape of aero-fin is used in the path of stress flow which helped to regulate stress flow by redistributing the lines of force.
7. Axial Direction: For node 1,2,3,4 as load increases there is decrease in acceleration with decrease in value if maximum frequency attainted for corresponding Maximum acceleration.
8. Horizontal Direction: For node 1,2,3,4 as load increase there is initial decrease in Acceleration to its minimum and then again starts increasing with same behaviours in trends of corresponding maximum frequency value.
9. Vertical Direction: For node 1,2,3,4 as load increase there is initial decrease in Acceleration to its minimum and then again starts increasing with same behaviours in trends of corresponding maximum frequency value.
10. Vertical Direction: For node 5, 6 as load increase there is initial decrease in acceleration to its min and then again starts increasing with same behaviours in Trends of corresponding maximum frequency value.
11. From the test result and FEA results it is observed that the results are found satisfactory and within the range.

Future Scope:

In the present study only two artificial defects (crack and decrease in tooth height) have been consider. Natural pitting, bending and wear can also be considered for further study.

1. In the present study only three parameters speed, crack size and decrease in tooth height have been varied. For further study load variation, lubricating oil and multi hour test running can also be considered.
2. In the present study no further advanced signal processing technique has been used. For the future work FFT and RMS. value can also be considered.
3. Similar work can be performed on different types of other gear and gear boxes for reduction in vibration caused by rotating machinery parts.
4. Observation results obtained by FFT can be validated with mode shape analysis using various Finite element software like ANSYS to get more accurate results.
5. Various metrological methods can be implemented for online inspection of rotating machines on basis of results obtained by above experimental work, for suitability to low skilled workers.
6. This kind of project work proves to best suited method in field of NVH Analysis in various automobile sectors.

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