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"Gear fault Types and Condition Monitoring Indicators for Gearbox" – A Combined Assessment

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Abstract— Lot of research is going in area of condition monitoring and fault diagnosis of gearboxes. Also it has been witnessed that there is no paper which combines the information about gear faults of gearbox and faults identification clues, condition monitoring statistical indicators. In order to develop new condition monitoring indicators, the information of gear faults is important. The condition indicators provide particular information regarding the health of machine or machine components. The intent of this paper is to assess and summarize literature to give a noble reference for firsthand researchers in the area of condition based monitoring of gearbox and in this way to enhance the research in gearbox development.

The experiment shows, at 1100 rpm speed and at healthy gear pair the value of Equivalent sound pressure level is 87.4 db. Maximum equivalent sound pressure level is 92.1 db for faulty condition.

Keywords— condition monitoring, gear faults, faults identification clues, statistical indicators, gearbox development

I. INTRODUCTION

Condition based monitoring is a maintenance program which endorses maintenance decision based on the actual condition or health of the equipment [12]. In data acquisition one collects all deta and store the deta in computer. Data processing: Once the data is collected same is to be processed in terms of charts or graphs. [15].

Condition monitoring data are the measurement data which gives the information about to the condition of machine or state of the physical set up or component e.g. vibration, temp, pressure, strain, noise[9].Vibration is the mostly used parameter to monitor the health of the gearbox elements. Vibration measurement, acoustic emission technique and oil analysis methodology can be adopted in condition monitoring of the machines or machine equipments.

The acceleration and stress are the parameters used for drawing conclusions [4]. Shen Guoji, Stephen Mclaughlin et. al. proposed the outline about the usage of bispectrum analysis. In this paper model is prepared to reveal the characteristics for the faulty gear vibration [5].The study is carried on the helicopter gearbox.

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II. LITERATURE REVIEW

Vikas Sharma and Anand Parey in review paper addressed the condition indicators domain wise [3].The structure of the fixed axis gearbox is also presented in this paper.

Some issues in the condition monitoring domain are mentioned and scope of further research is also included. Weigang hu, Zhiming Liu et. al. in paper entitled, "Fatigue fai;ure analysis of high speed train gearbox housings" investigated the fatigue crack growth in high speed train gearboxes. Different techniques have been employed to obtain failure modes of gearbox housing.

J Parra, Cristian Molina Viena in paper studied the different frequencies associated with the planetary gearbox. This is carried out for healthy and faulty gear condition. Two different models are considered phenomenological and lumped parameter model. The lumped parameter model study is depends on the solution of the equations[6]. Adrian Cubillo et. al. reviewed the concept of physics based models for prognostics. The different available models for degradation system are represented. The wear model is mentioned in this paper along with the information of following degradation mechanism like creep, fatigue, wear and fatigue and creep [7].

Jin Jiang Wang et. al. proposed virtual sensing technique for condition monitoring. This technique is validated experimentally with gear wear [10]. Chan II Park prepared the model for a degraded gear system with shaft, bearing and gear. Noise characteristics were investigated for different conditions like change in input torque, change in material of plate and change in shaft diameter [11].

Manik Chandra and Reza Langari in paper used the K nearest algorithm and neural network for investigation of gear stiffness degradation [13]. Kiran Vernekar et. al. presented wavelet transform for diagnosis purpose. In this paper investigation is carried out on gear of IC engine and vibration signals are acquired at healthy and faulty gear condition [16]. Zhixiong Li et. al. estimated bispectrum analysis and Artificial Neural Network method. This technique of fault recognition has been implemented for marine propulsion system[18]. Chee Keong Tan and David Mba concluded that, huge opportunities exist for improvements in acoustic emission technique. It has been observed that, fault detection with AE technique is complex [20]. S H Gawande, D K Korade proposed method of phasing for spur gear arrangement for vibration reduction. RMS velocity and RMS acceleration are the parameters used for vibration measurement [21]. Naim Bayder et. al. proposes wavelet transform tool which is capable to determine progressing gear fault condition[22]. Ruoyo et.

al. presented a methodology of fault detection with the help of acoustic emission sensor for split torque gearbox.By studying the acoustic emission burst, exact location of gear fault can be determined [23].
Alfonso Fernandez Del Rincon, Fernando Viadero et. al. presented an model to investigate the changes in mesh stiffness when the gears are subjected to cracks and pits [25].
Wang W presented a novel technique of resonance demodulation. This approach is used for gear tooth cracks investigation [26]. Ma H., Pang X., Feng R et. al. concluded that, the gear crack reduces the gear body rigidity, so that there is reduction in stiffness[27].

III. GEAR FAULT TYPES

There are many factors are responsible for the failure of gearbox or its components. These include bearing failure, misalignment, overload or unexpected loads, poor lubrication, shaft imbalance, contamination by water or debris, improper material and manufacturing defect [19].
In below diagram different gear failure modes and degradation mechanisms are shown. [7]

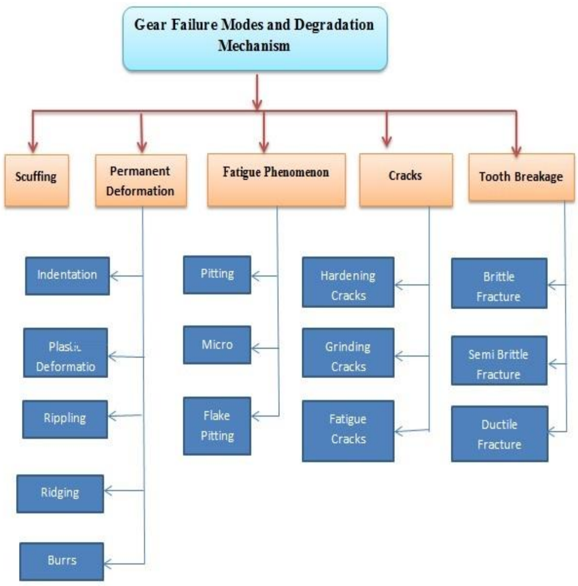


Figure 1 Gear failure modes and degradation mechanisms

Wear - It is a superficial phenomenon in which some material of gear tooth surface is removed during the torque transmission process.
Pitting - Pitting takes place due to fatigue failure mechanism of the gear tooth. It takes place when the gears are subjected to repeated loading condition. In this process the surface material of the tooth gets removed and finally it forms the pit. The pit increases the stress magnitude at certain points and so on there is stress concentration took place in these areas. Though stress concentration is present but still gear completes million of working cycles before they actually fail. The pitting is classified as slight , medium and severe based on the area covered by the pits over the tooth surface as 6.3%, 27.8% and 41.7% respectively[17].The slight, medium and severe pitting conditions are shown in the below images[8].

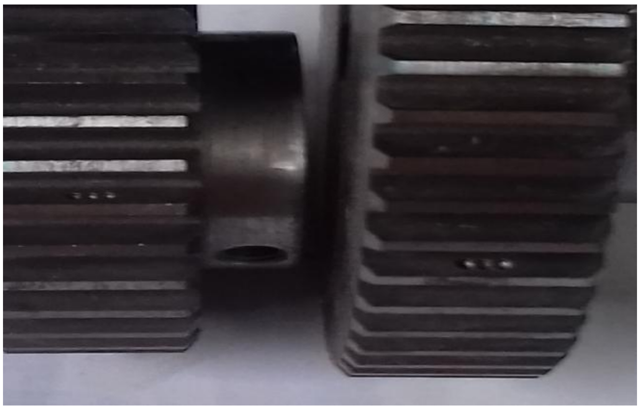


Figure 2 Slight Pitting

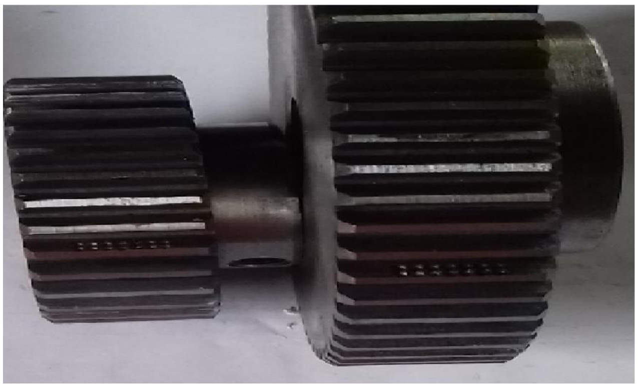


Figure 3 Medium Pitting

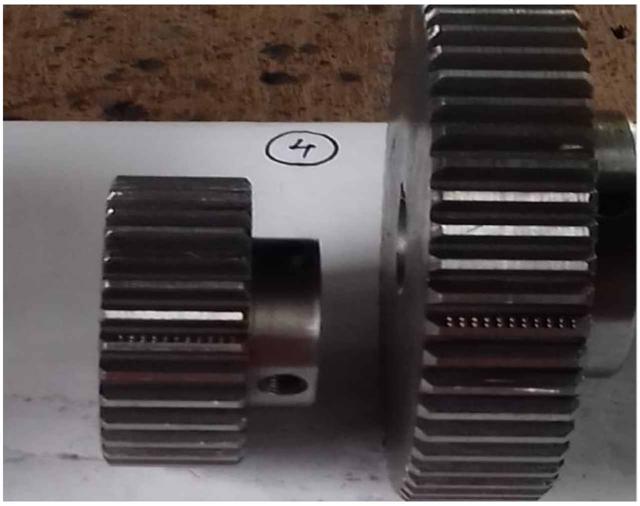


Figure 4 Severe Pitting

Fracture - High overload may finally results in tooth breakage. The high magnitude impact load or static load may be cause for fracture. Repeated load may cause the low cycle fatigue.
Corrosion: The lubricating oil in the gearbox carries out the excess heat but at the same time their chemical action is responsible for corrosive wear of the gears and other elements.
Destructive Scoring: is identified by radial scratch and tear marks on the gear.
Localized Scoring: As the name indicates the scoring took place due to application of load at definite area of the gears. This type of scoring does not observed across the full face width of mating gear.

Frosting: Frosting is observed at the initial stages of scoring. Usually the dedendum section of driving gear is the first to show signs of surface distress, even though frosting can primary be evidence on the addendum section.
Overload Breakage: An over load fracture results in a stringy, fibrous break showing evidence of having been pulled or torn apart.
In harder materials the break has a finer stringy appearance but still shows evidence of being pulled apart abruptly.
Random Fracture: Gear tooth breakage is usually related with the root fillet section of gear tooth; on the other hand breakage failure can occur in other portion of gear tooth. At times, the tip of the gear tooth will break away or big chips will fatigue away from the end of tooth.
Cold Flow: The gears with higher hardness are less prone to cold flow failure. The accurate gear profile and tooth spacing are the conditions that will reduce the occurrences of the cold flow defect.

Rippling: It is not considered if it is at initial stage. If the gears with soft materials are case hardening with proper treatments then rippling can be prevented.
Rim and Web Failure: the rim of gear usually fails between two adjacent teeth. Cracks propagate through the rim and into the web. Sometimes, crack appears in web near the rim and web junction without disturbing the rim itself.
Ridging: It has been identified by peaks and valleys formed due to sliding velocities between two mating gears. Ridging is present in soft material in case of high contact stresses of mating surfaces.

IV. FAULT DIAGNOSIS CLUES

Vibration of gear changes as due to the eccentricity, misalignment or the gear wear. Bevel gear creates axial vibration and spur gear creates more radial vibration [2]. In case of gear pair we can expect one pick for turning speed of gear and another for the pinion.
One can get the sidebands near the gear mesh frequency. The reason for this is the frequency modulation or the amplitude modulation. These are also known as cyclic variation.
Amplitude of side bands, number of side bands and distance between sidebands gives the condition of the faults. One may see the sidebands at twice gear mesh frequency or thrice gear mesh frequency. The level of tooth mesh frequency is dependent on the alignment of the shaft carrying the gears and the load acting on these gears. Eccentric gear produces greater modulation and higher amplitude sidebands.
Time wave analysis is very important tool in gear analysis. It gives you the exact truth It will tell what exactly going on inside the gearbox. Spikes in time wave analysis indicates the damaged tooth. In time wave analysis sampling rate shall be fast enough so that results displayed will be closer to the actual one[28].

V. CONDITION INDICATORS

The accelerometers can be used to obtain the vibration characteristics. These attained signals are in time domain and with the help of FFT (Fast Fourier Transform) it can be transformed into the frequency domain so that interpretation of signal becomes convenient. There is always change in energy whenever any fault took place in the gear. Different Condition indicators which are in use are given below [4][24].
RMS – Root mean square is the indicator of vibration amplitude and energy present in the signal in time domain. The Root mean square (RMS) is defined by taking the square root of the average of the sum of the squares of the signals present.

$$X_{RMS} = \sqrt{}x_1^{2} + \sqrt{}\ x_2^{2} + \sqrt{}\ x_3^{2} \ldots / N$$

Crest Factor- Crest factor is the ratio of highest value to its root mean square (RMS) value of the signal.

$$C_f = X_{Max.} / X_{RMS}$$

Standard Deviation-It is the total of deviation of the signal about its mean value.

$$\sigma = \sqrt{}\ \ \Sigma(x_1^{2} - x)^2$$

Variance – It is the square of the standard deviation.

$$\text{Variance} = \sigma^2$$

Kurtosis- It describes how flat or peaked the distribution spread. It is measure of the peakedness of the signal. If the gearbox health is in good condition then kurtosis values will be less and this value will be higher when the damage was initiated in the gearbox.
Form Factor – It is defined as the ratio of Root Mean Square (RMS) of the signals divided by mean value of the signals.

$$S_f = X_{RMS} / X_{Mean}$$

Shape Factor- It is used to represent the time series distribution of the signal in the time domain .
Energy Ratio- It is defined as the root mean square (RMS) of the difference signal divided by the root mean square (RMS) of the signal comprising the regular meshing components.

$$ER = \sigma(d) / \sigma(r)$$

σ(d)=standard deviation of the difference signal
σ(r)= standard deviation of the regular signal
Sideband Index- it is defined as the average amplitude of sidebands of the fundamental gear mesh frequency.
Energy Operator (EOP)-Damage gear produces an impulse and that is supported by energy operator.
Zero Order Figure of Merit (FM0) – The Stewart had introduced this indicator in 1977. This is used to indicate major faults in a gear mesh. Comparison of the maximum peak-to-peak amplitude of the signal to the sum of the amplitudes of the mesh frequencies can help to find out the changes in meshing pattern.
M6A- This indicator was introduced by Martin in 1989 to reveal the surface damage of machine or machine components. M6A indicator can easily sense the peaks in the difference signal.
NA4- This parameter was given by Zakrajsek, Townsend, and Decker in 1993. It has been a good fault indicator for damage occurrence in the gear.
NB4- It was presented in 1994 by Zakrajsek, Handschuh and Decker to reveal out localized gear tooth fault. The gear fault will generate momentary load fluctuations. These fluctuations can be studied by observing the envelope of the signals.

Wear - It is observed by analyzing the spectrums that in majority cases at 1X RPM (X is the angular speed of shaft) frequency amplitude reduces at 2X RPM (X is the angular speed of shaft) amplitude increases or decreases mostly no change or decrease in amplitude is observed at Gear Mesh Frequency (GMF) 1 and no alterations are noted at Gear Mesh Frequency (GMF) 2. Variations in side band frequencies are observed.

Pitting- Due to pitting, there are some variation are observed in side band frequencies.

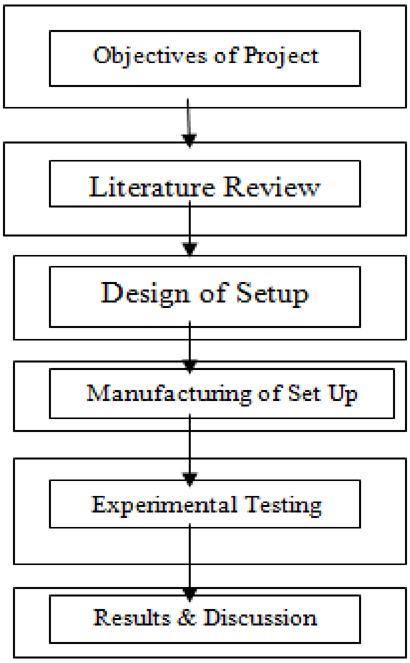
Corrosion- It has been observed by investigating the spectrums that in utmost situations at 1X RPM (X is the angular speed of shaft) frequency, amplitude reduces at 2X RPM (X is the angular speed of shaft) amplitude rises typically, no change or increase in amplitude is observed at Gear Mesh Frequency (GMF) 1 and amplitude remains almost steady at Gear Mesh Frequency (GMF) 2. Deviation in side band frequencies has been noted.[2]

Crack Gear- It is observed by studying the spectrums that in most cases at 1X RPM (X is the angular speed of shaft) frequency amplitude increases at 2X RPM (X is the angular speed of shaft) amplitude increases,

Secondly no variation or decline in amplitude is observed at GMF 1 and amplitude remains constant at GMF 2. Disparity in side band frequencies has been noted.

Crack Pinion- From the vibration spectrum it has been noted that, at 1X RPM (X is the angular speed of shaft) frequency amplitude rises, at 2X RPM (X is the angular speed of shaft) amplitude increases or may decreases. Secondly increase in amplitude is observed at Gear Mesh Frequency (GMF) 1 and amplitude remains almost the same at Gear Mesh Frequency (GMF) 2.

VI. METHODOLOGY



Flow chart for Methodology

VII. EXPERIMENTATION

Design of Experiment :

The test rig is designed to carry out experimentation to detect faults namely slight pitting, moderate pitting and severe pitting in a gearbox. In the experimentation, acoustic response measured from the gear box is analyzed to detect faults. For this analysis gearbox rotates at loading condition and varying speed of induction motor. Varying load has been applied on the output shaft of the gear box by means of a Rope – Brake Dynamometer. The motor speed has varying by the AC dimmer stat. The acoustic emission response from the gear box has been recorded by an analyser.

Figure 5 Experimental Set Up

The component of design setup is as follows:-

i) Motor: - It consists of a 0.5HP AC derive motor coupled with gearbox. It transmit the power to gearbox

ii) Gear Box: - It consists of single stage spur gearbox which is selected for the detection and advancement monitoring of faults. The Specification of Gear box is as follows:

iii) Dynamometer: - The power is transmitted from motor to dynamometer through gearbox. The Rope Brake dynamometer is used for applying load on gearbox.

iv) Microphone: -For noise measurement Microphone is place away from gearbox. Here, Free field polarized microphone was used to measured noise of gearbox.

v) Svantek 958 four channels Analyser: - It is used to store the data which is in Acoustic spectrum form for further analysis. The readings are taken for healthy gear different condition of gears having various faults with different load conditions. This data stored in Analyser.

Design of experiments is a method of designing experiments, in which only selected number of experiments are to be performed. After performing the final experiments results are shown in below table.

VIII. RESULTS & RESULT ANALYSIS

Sr. No.	Gear	Pinion	Speed in RPM	Load in KGs.	L eqi.(dB)
1	Healthy	Healthy	1100	0	87.400
2	Healthy	6.3% pitting	1200	1	89.175
3	Healthy	27.8% pitting	1300	2	91.350
4	Healthy	41.7% pitting	1480	3	91.800
5	6.3% pitting	Healthy	1200	2	89.900
6	6.3 % pitting	6.3% pitting	1100	3	90.050

7	6.3% pitting	27.8% pitting	1480	0	90.770
8	6.3% pitting	41.7% pitting	1300	1	91.350
9	27.8% pitting	Healthy	1300	3	91.500
10	27.8% pitting	6.3% pitting	1480	2	92.000
11	27.8% pitting	27.8% pitting	1100	1	90.600
12	27.8% pitting	41.7% pitting	1200	0	90.770
13	41.7% pitting	Healthy	1480	1	90.350
14	41.7% pitting	6.3% pitting	1300	0	90.770
15	41.7% pitting	27.8% pitting	1200	3	92.150
16	41.7% pitting	41.7% pitting	1100	2	91.800

The identification of gearbox Acoustic emission in terms of equivalent sound pressure level is introduced. Minimum sound pressure levels have been observed for healthy condition of gears. Severe pitting can be easily measured by acoustic parameters

IX. CONCLUSION

Early detection of fault is possible by using acoustic emission. By experimental analysis, at 1100 rpm speed and at healthy gear pair the value of Equivalent sound pressure level is 87.4 db. Maximum equivalent sound pressure level is 92.1 db for faulty condition.

Significant progress in condition monitoring of gearbox can be made with the combined information of gear faults types and condition monitoring indicators.

Following points can be concluded based on the literature survey done:

1. In most of research articles conditions monitoring indicators are focused to investigate specific type of gearbox fault like the fatigue cracks. So there is the scope to work on other gear fault types.
2. In few papers the pitting type failure is considered but investigation is done with the help of computational simulation software. There is the scope to perform actual experimentation.
3. Noise (dB) is the least addressed condition monitoring indicator as compared to vibration parameters. Noise is having potential to indicate the health of machine without making the contact of sensor with actual set up.
4. Condition monitoring clues are outlined in this paper this will lead to development of new condition monitoring indicators in this area.

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