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Condition Monitoring Of Gearbox Based On Lubrication Oil Analysis

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Abstract: Machine downtime is a significant challenge in industries, primarily caused by misalignment of parts, equipment failure, wear of gears, and unexpected maintenance issues. Condition monitoring is essential to detect machine faults and prevent instability and improper functioning. This project focuses on the condition monitoring of gearboxes using lubrication oil analysis and signal processing techniques. Vibration analysis, known for tracking dynamic conditions, and viscosity analysis, crucial in assessing the health of lubricating oils, are employed. Lubricating oil samples were collected every 100 hours, and corresponding vibration signals were acquired. Time domain and frequency domain analyses were applied to extract defect information. The lubrication regime analysis indicated that deviations in oil viscosity trends corresponded with gear condition changes. Specifically, the 9th multiple of the gear mesh frequency at around 4000 Hz showed significant dominance, highlighting gearbox issues. The integration of viscosity analysis with vibration signal techniques enhanced gear health assessment, enabling timely maintenance and preventing severe damage. Thus, lubrication oil analysis and vibration signals are recommended for effective gearbox condition monitoring, improving overall machine reliability and reducing maintenance costs.

1. *Keywords* - Condition Monitoring, Lubrication Oil Analysis, Vibration Analysis, Gearbox Fault Detection

I. INTRODUCTION

In modern industries, the reduction in productivity and increase in maintenance costs are primarily due to faults in machinery. Predictive maintenance techniques are widely employed to mitigate these costs and enhance production efficiency. Given that industrial machinery often operates continuously, unexpected downtime, particularly in rotating machinery, can significantly hinder production. Most machinery incorporates gearbox assemblies, making it crucial to develop effective condition-monitoring techniques to prevent malfunction and damage during operation. Early fault detection is essential to avoid severe damage that could lead to system-wide failures. Condition monitoring of gearboxes is a proactive strategy aimed at maintaining their health and performance. This technique involves real-time monitoring to identify potential issues before they escalate into major problems, thereby facilitating proactive maintenance and extending the gearbox's lifespan. Continuous data collection and analysis from various sensors allow for the detection of changes in gearbox behaviour, providing early warnings of potential issues. Advanced algorithms and predictive models play a pivotal role in offering valuable insights into gearbox performance, assisting in informed maintenance and repair decisions. Consequently, condition monitoring proves to be a more efficient, cost-effective, and reliable approach to gearbox maintenance, leading to reduced overall maintenance costs. Gears are fundamental components in mechanical systems, essential for transmitting power and motion between machine parts. Their widespread use in industrial applications underscores the importance of ensuring their reliability and durability. Properly functioning gears are crucial for the optimal performance of machinery, and any fault or wear in gears can lead to significant operational disruptions. Gear failure is a common issue in industrial machinery, often resulting from factors such as misalignment, improper lubrication, excessive loads, and manufacturing defects. These failures can lead to increased vibration, noise, and eventual breakdown of the machinery. Understanding the causes of gear failure is vital for developing effective monitoring and maintenance strategies. Misalignment of gears, for instance, can cause uneven distribution of forces, leading to accelerated wear and eventual failure. Similarly, inadequate lubrication can result in increased friction and heat generation, further contributing to gear degradation. Several techniques are employed for condition monitoring of gearboxes, each with its specific advantages and applications. Vibration analysis is a structured approach to tracking and analysing the dynamic conditions of machine parts. By monitoring vibrations, it is possible to detect anomalies indicative of potential faults in the machinery. This technique is particularly effective for identifying misalignments, imbalances, and bearing defects. Oil analysis is a critical component of condition monitoring, particularly for assessing the health and performance of lubricating oils used in machinery. This analysis involves measuring the resistance to flow of the oil and providing insights into potential issues such as contamination, degradation, and inadequate lubrication. Acoustic emission analysis monitors the high-frequency sounds emitted by materials under stress. This technique can detect cracks, leaks, and other structural defects in machinery components. Sound analysis involves monitoring the noise generated by machinery during operation. Changes in sound patterns can indicate the presence of faults or abnormal operating conditions. Thermography uses infrared imaging to detect temperature variations in machinery components. Abnormal temperature patterns can signify issues such as overheating, inadequate lubrication, or excessive friction. Lubrication oil analysis is an effective method for condition monitoring of gearboxes. Viscosity analysis, in particular, provides valuable information about the health of the lubricating oil and, by extension, the condition of the gearbox. Regular collection and analysis of oil samples can reveal trends and deviations that indicate potential faults. Integrating viscosity analysis with vibration signal techniques enhances the overall assessment of gear health, enabling timely maintenance actions and preventing severe damage.

II. LITERATURE SURVEY

M. Lokesha et al., (2011) The results of using FFT-based vibration signal processing, Morlet wavelet enveloped power spectroscopy, and Laplace wavelet enveloped power spectroscopy at different stages of an induced gear defect are contrasted. To show the superiority of Morlet wavelet and Laplace wavelet-based wrapped power spectra for problem diagnosis in gear, the suggested application contrasts the considerable increase in vibration amplitude at GMF and their 1xRPM of sidebands compared to the FFT power spectrum. The recommended diagnostic technique is less susceptible to changes in operational speed, lubrication, and load than conventional FFT analysis. By employing the proper de-noising technique, the extraction of a gear's defective characteristic may be significantly enhanced [1].

David He et al., (2012) The authors of this work describe an efficient approach for split torque gearbox gear defect location identification utilizing AE sensors. This approach processes the AE sensor signal using a wavelet transform, which helps to estimate when the AE bursts will arrive at various places. The wavelet transform's parameters were improved using an ant colony optimization approach. First, experiments with broken pencil leads were used to establish the data gathering system's sampling rate. The sampling rate of 500 kHz was chosen after careful consideration of the Fourier spectra, RMS, and peak SNR of the AE bursts from the pencil lead break tests. To pinpoint the location of the damaged gear, AE sensor readings were concurrently gathered at the locations of the healthy and damaged output drive gears. The distribution of the AE burst arrival times from the damaged gear that were observed clearly showed the efficacy of the methods used [2].

Jussi et al., (2012) The writers of this research have concluded that vibration analysis is employed to keep an epicyclical gearbox in a hydraulic power plant under check. Vibrations with frequencies under 1000 Hz were extremely well received by the vibration rate. Acceleration and its higher derivatives, which also provided additional information on the higher frequencies, provided an even better solution. The conclusion that the vibration speed is insufficient to monitor the condition of the gearbox in issue may be drawn from the very high rotation speed of the second stage. To provide a better responsiveness to changes in gearbox condition and its higher-order derivative should also be employed [3].

Adam Czaban et al., (2013) The paper begins by providing a brief overview of the factors that affect the viscosity of oils, including molecular weight, structure, and additives. The authors then present the results of their experiments, which were conducted using a rheometer to measure the viscosity of the oils at different temperatures and shear rates. The results of the experiments showed that the viscosity of the oils decreased with increasing temperature and increasing shear rate. The authors also found that the addition of certain additives, such as viscosity improvers, could help to stabilize the viscosity of the oils over a wider range of temperatures and shear rates [4].

Anand Prabhakaran et al., (2013) The paper discusses the different techniques that can be used to analyze wear debris, including automatic particle counters, ferrography, ICPAES, SEM, and EDAX. The authors then present the results of their study, which showed that the concentration of wear debris in the used lubricating oil increased over time, and that the type of wear debris also changed [5]. They also found that the use of a combination of techniques could provide a more comprehensive assessment of the condition of the turbine. The paper concludes by discussing the implications of the findings for the condition monitoring of steam turbine-generators. The authors suggest that the use of wear debris and particulate contamination analysis can be a valuable tool for detecting early signs of wear and tear, and that this can help to prevent catastrophic failures.[2]

Riku-Pekka Nikula et al., (2013) A technique to real-time condition monitoring of an epicyclic gearbox in a hydroelectric power plant is presented in this work. An epicyclic gearbox must have early and reliable fault detection since a failure might result in a lengthy out-of-service period. The hydroelectric power plant is utilised to supply the electrical system with load-following electricity. When power is generated, the weight on the gear changes, but the spinning speed remains constant. Accelerometers installed atop a two-stage epicyclic gearbox are used to collect data from the plant's various operating stages. First, it is determined how the load affects the characteristics of the vibration signals. In this work, the characteristics include phase-randomized spectrum components and amplitude spectrum components. The features' load-related control limits are then determined. Following identification, an independent test set of data is used to test the condition monitoring technique. The effectiveness is also seen when fictitious fault signals are introduced to the real measurement data [6].

Kiran Vernekar et al., (2014) Two signal processing techniques for detecting gear problems in internal combustion engines are provided in this paper. These are conventional vibration spectrum analysis and continuous wavelet transform. A fault detection engine test rig is built to gather vibration data from both a healthy and a simulated damaged gear state for experimental research.

In both ideal and simulated faulty gear scenarios, the vibration signals from the internal combustion engine are collected using an accelerometer. In this study, both the traditional vibration spectrum analysis and the morlet wavelet are used as a continuous wavelet transform (CWT) for diagnosing gear problems. The results of the experiments demonstrate that the recommended method is effective in locating gear defects [7].

III. OBJECTIVES OF RESEARCH WORK

The main aim of the project is to monitor the condition of gear based on Lubrication oil analysis and Vibration analysis

- To assess the gearbox condition based on Lubrication regime analysis by assessing the viscosity and shear rate of the lubricating oil sample.
- To monitor/detect the condition of gearbox using Vibration signals by Time domain plots and Frequency domain plots.
- To correlate the condition of the gearbox with Vibration analysis and Lubrication regime analysis.

IV. RESEARCH METHODOLOGY

The methodology is developed by assessing the project, tools, requirements, etc., and are deduced such that it fulfills the objectives defined. It is designed primarily to regulate the overall project management process through efficient decision-making and for effective resolution.

3.1 Methodology of Research work

Methodology is essentially a compilation of the approaches, sequences, practices, and processes used in the particular project. In this part, we go through the tools we utilised for our study as well as the procedure for using the FZG Gear test setup shown in figure.

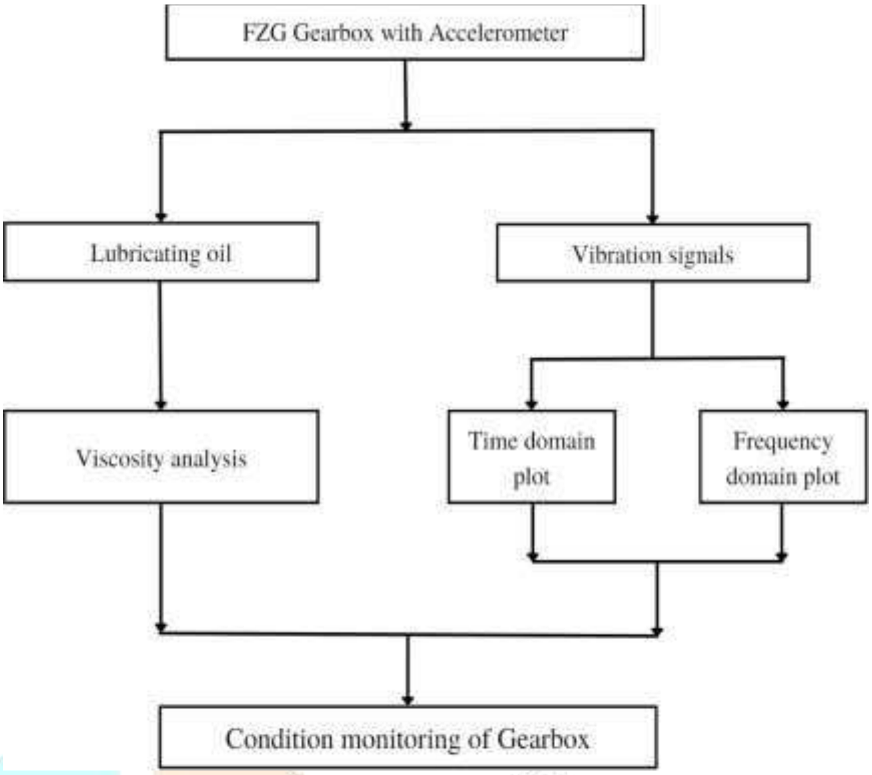

Fig1.: Methodology of Condition monitoring of FZG gearbox

FZG test rig gearbox was made to run at the load condition of 50N and the gear rotates at 600 RPM (10Hz), the corresponding pinion rotates at 963.95 RPM (16Hz). The Vibration signals were acquired using accelerometer and they were converted from analogy to digital by DAQ system and stored in computer. These acquired vibration signals were analyzed using appropriate signal processing techniques such as:

- Time-Domain Analysis: It involves examining the raw vibration signals in the time domain. This includes analyzing parameters such as amplitude to understand the general behaviour of the system. It demonstrates how the signal's amplitude fluctuates over time.
- Frequency-Domain Analysis: In the frequency-domain analysis, the vibration signals are transformed from the time domain to the frequency domain using Fast Fourier transform. This enables the identification of specific frequencies present in the signal and the determination of their magnitudes. The vibration signals are being sampled for a time period from 0 sec to 1 sec where 25600 samples are being acquired and sampling frequency is 25600 Hz.

3.1.1 Gear mesh frequency

Gear mesh frequency (GMF) is one of the fundamental parameters for vibration analysis. Gear mesh frequency is the product of number of teeth on gear and shaft's rotational speed [8].

fm = z. fr……………………………………………………………………………………1.

3 where z is the number of teeth on gear and fr is rotational speed of shaft.

In this experiment, the gear mesh frequency turns out to be fm = 45*10 = 450Hz. GMF is crucial for analysing frequency domain plots and it is mentioned in upcoming results and discussion chapter.

The methodology for viscosity analysis of lubricating oil includes the following steps:

- Sample Collection: A representative sample of the lubricating oil from the gearbox is collected for every 100 hours and placed in a clean, sealed container for analysis.
- Sample Preparation: The oil sample is prepared for analysis by stirring the samples and precautions are taken in order to avoid any contamination for accurate analysis.
- Laboratory Analysis: The oil sample is analysed using for viscosity, shear rate, shear stress by employing Rheometer instrument.

- Data Analysis and Interpretation: The results of the laboratory analysis are interpreted to determine the condition of the lubricating oil and the gearbox. The results are compared with previous results to identify any changes or trends.

3.2 Experimental Setup

The experimental setup for condition monitoring includes FZG gearbox, accelerometer, DAQ system used to experiment. They are explained in the below subsections.

3.4.1 Experimental setup of FZG Test Rig

The vibration investigation of the gearbox was carried out using a back-to-back power recirculating type oil lubricating FZG spur gear Test rig. As seen in figure 2, it comprises slave and test gear pairs positioned on the ends of two parallel shafts. The load is applied to test gears using a lever arm and weights through a load clutch on one shaft. The oil sample will be collected at regular intervals of time as shown in figure

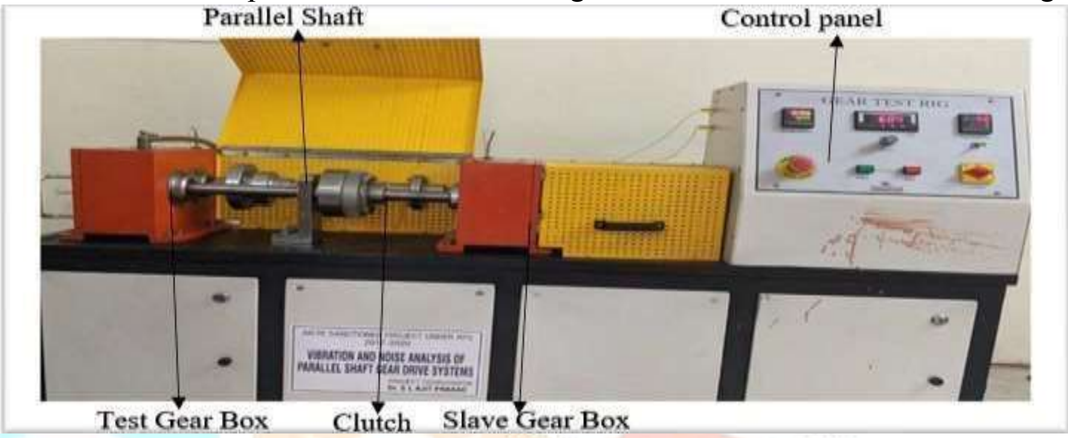

Fig. 2.1: Experimental setup

Fig. 2.2: Oil sample collection setup

The CTC AC102-1A accelerometer, which is positioned just above the pinion gear, was used to collect vibration signals in this study. For signal conditioning and processing of vibration signals, a 24 bit, DAQ system with four analogy input channels was used. The experimental setup including the sensor and data gathering system is shown in figure 4. The experiments were conducted at a speed of 600 RPM and vibration signals were acquired using accelerometer and DAQ system in a load condition of 50N. These acquired vibration signals were analysed using appropriate signal processing techniques such as FFT. Using acquired signal data time- frequency plots are generated in MATLAB software for monitoring the condition of gears.

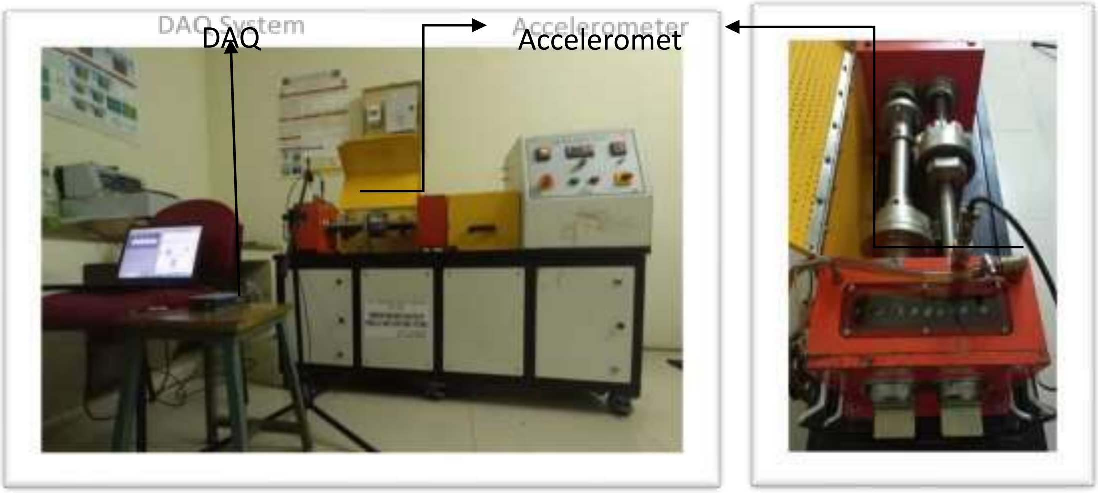

Fig. 3: Experimental setup with sensor and DAQ system.

V. RESULTS AND DISCUSSION

5.1 Introduction

Vibration signals from the FZG gear test rig are processed using FFT and results obtained from plots are discussed along with the viscosity analysis that includes shear rate vs. viscosity plots in this section. Variations in vibration patterns in different intervals of time are compared. Comparison between Time-Domain Analysis and frequency-domain Analysis are discussed.

5.1.1 Time Domain Analysis

A time-domain graph can also demonstrate how the signal's amplitude fluctuates over time. It involves analyzing the characteristics and behavior of a vibrating system based on the time-domain representation of the measured vibration signal. Vibration response in the time domain under different conditions of the gearbox is shown in Figure 5.

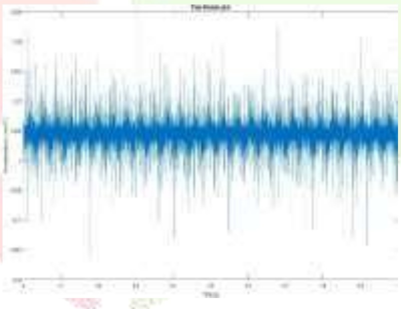

Fig. 4.1(a)

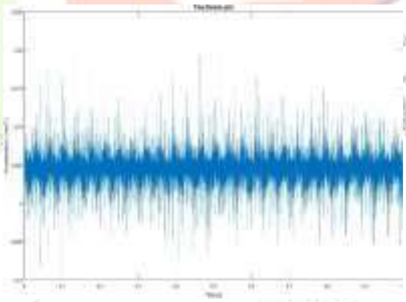

Fig. 4.1(b)

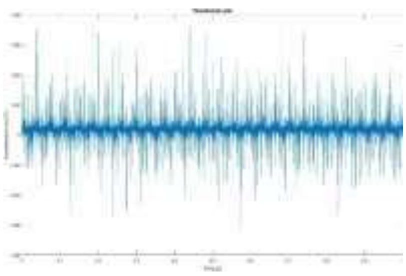

Fig. 4.1(c)

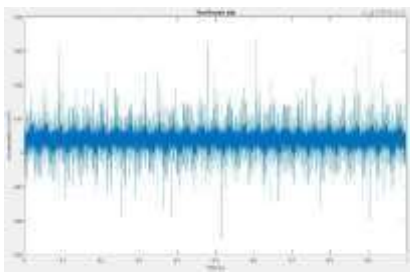

Fig. 4.1(d)

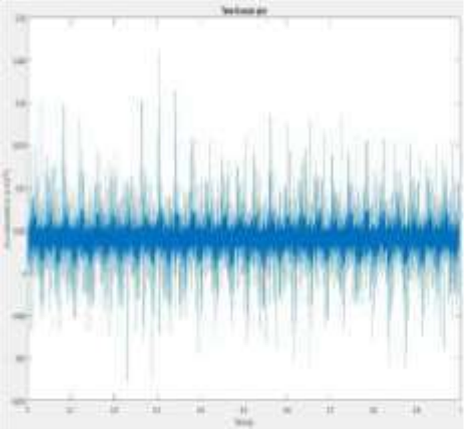

Fig. 4.1(e)

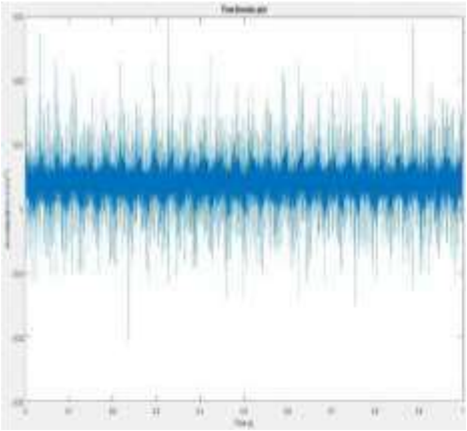

Fig. 4.1(f)

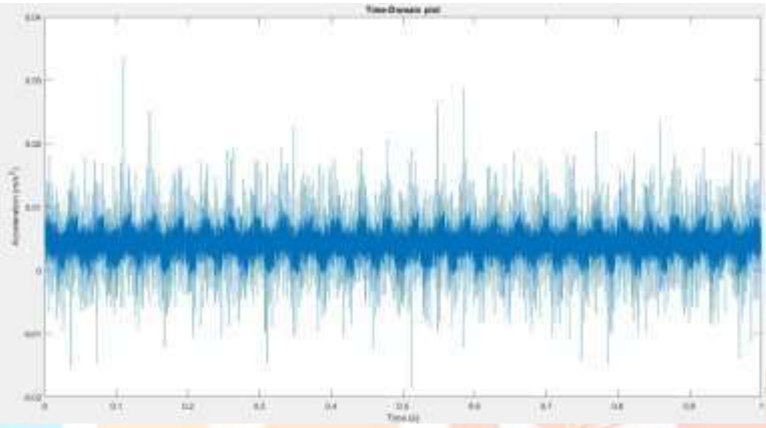

Fig. 4.1(g)

Fig. 4.1: Vibration response in time domain
4.1(a) load with 50N for 300 hours 4.1(b) load with 50N for 400 hours 4.1(c) load with 50N for 500 hours 4.1(d) load with 50N for 600 hours 4.1(e) load with 50N for 700 hours 4.1(f) load with 50N for 800 hours 4.1(g) load with 50N for 900 hours

The above figure shows the time series plot for the respective conditions on 50N for runtime of 300 hours ,400 hours, 500hours, 600 hours, 700 hours,800 hours and 900 hours. Minute differences in amplitude patterns can be seen in time domain analysis, but distinguishing the different gear situations is challenging. Hence, FFT is used to analyze the signal in terms of frequency components.

5.1.2 Frequency Domain Analysis

Time-domain signals under different conditions were converted to frequency-domain signals with sampling frequency of 25600 Hz as shown in figure

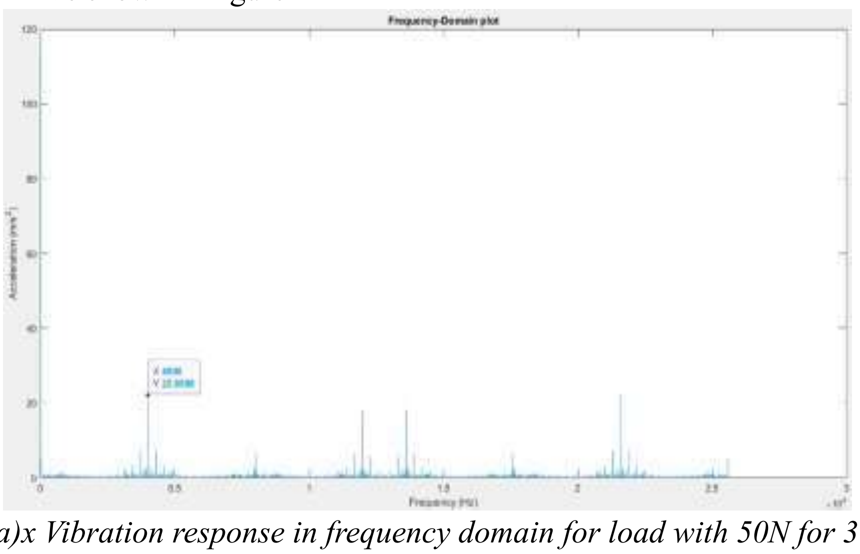

Fig. 4.2(a)x Vibration response in frequency domain for load with 50N for 300 hours

From fig. 4.2(a), it can be noticed that the value of acceleration is about 22.0598 m/s² at 300 hours running condition under the load of 50N.

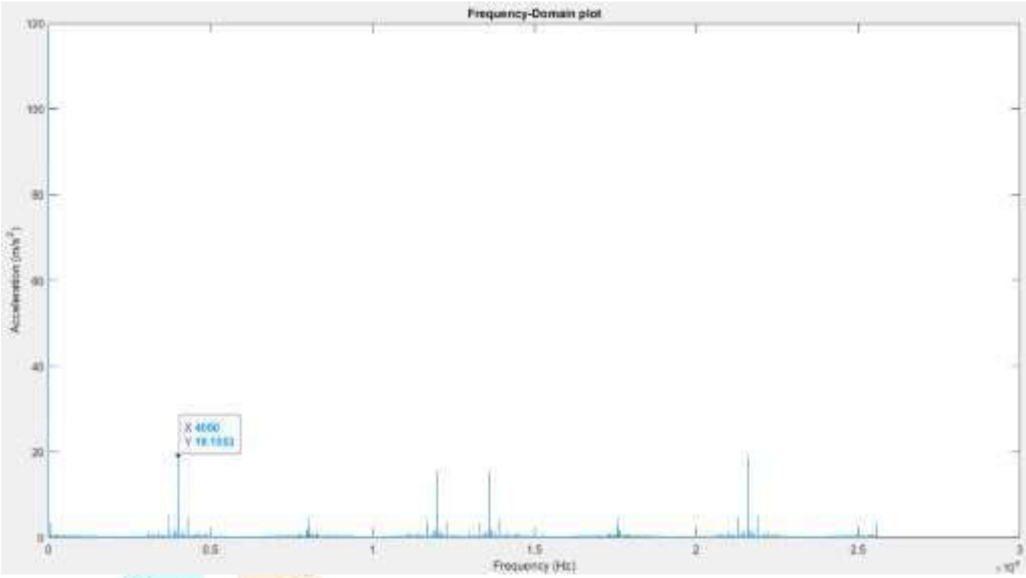

Fig. 4.2(b) Vibration response in frequency domain for load with 50N for 400 hours

From fig. 4.2(b), it can be noticed that the value of acceleration is about 19.1553 m/s² at 400 hours running condition under the load of 50N.

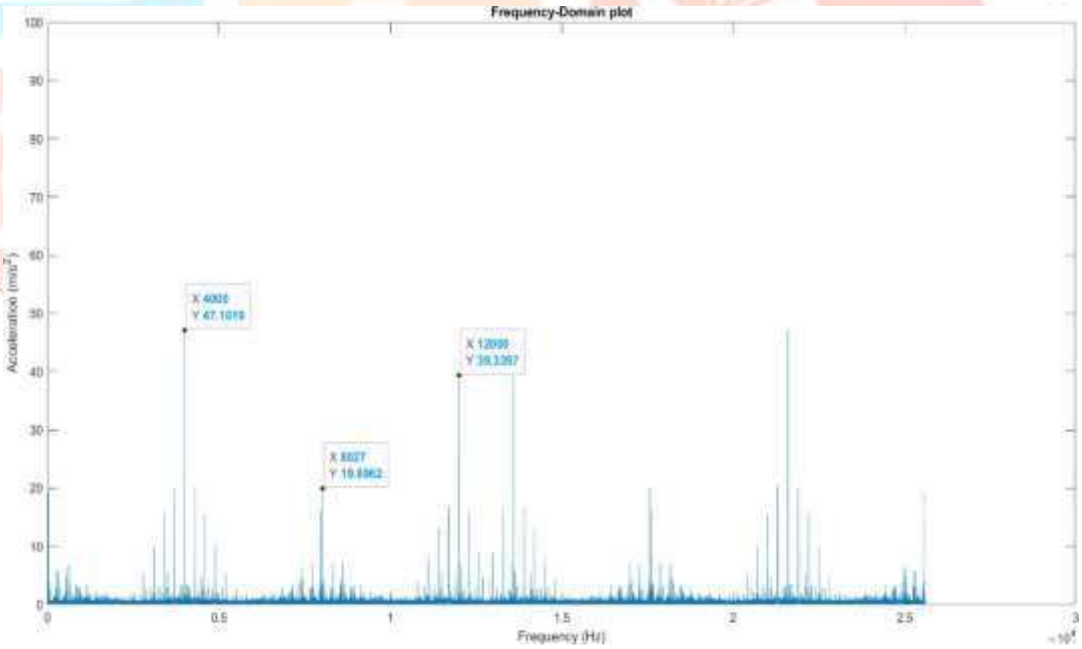

Fig. 4.2(c) Vibration response in frequency domain for load with 50N for 500 hours

From fig. 4.2(c), it can be noticed that the value of acceleration is about 47.1019 m/s² at 500 hours running condition under the load of 50N.

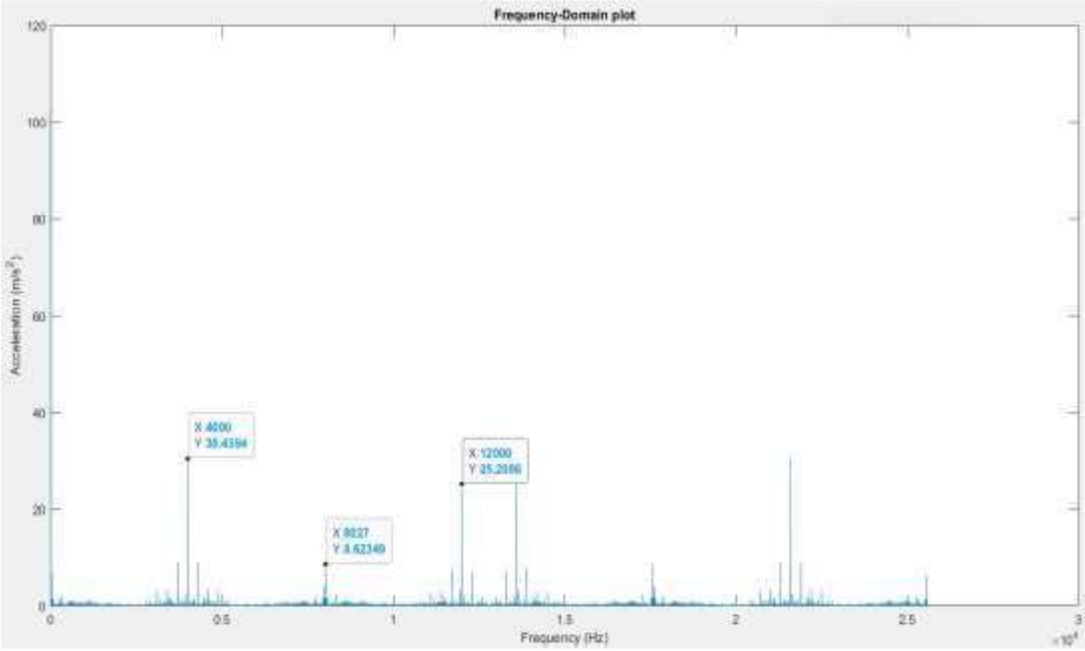

Fig. 4.2(d) Vibration response in frequency domain for load with 50N for 600 hours

From fig. 4.2(d), it can be noticed that the value of acceleration is about 30.4394 m/s² at 600 hours running condition under the load of 50N.

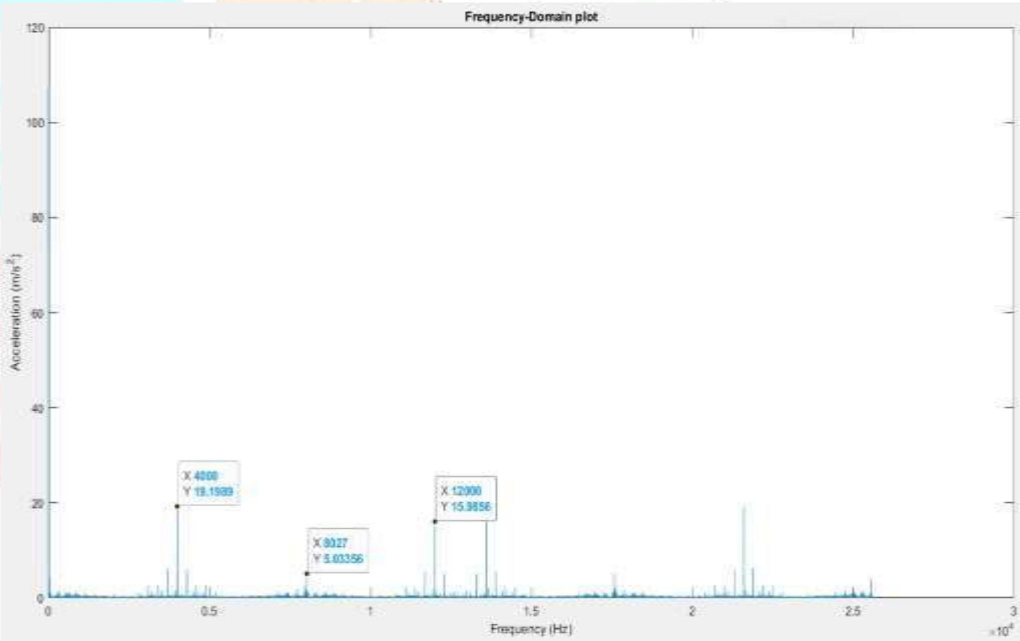

Fig. 4.2(e) Vibration response in frequency domain for load with 50N for 700 hours

From fig. 4.2(e), it can be noticed that the value of acceleration is about 19.1989 m/s² at 600 hours running condition under the load of 50N.

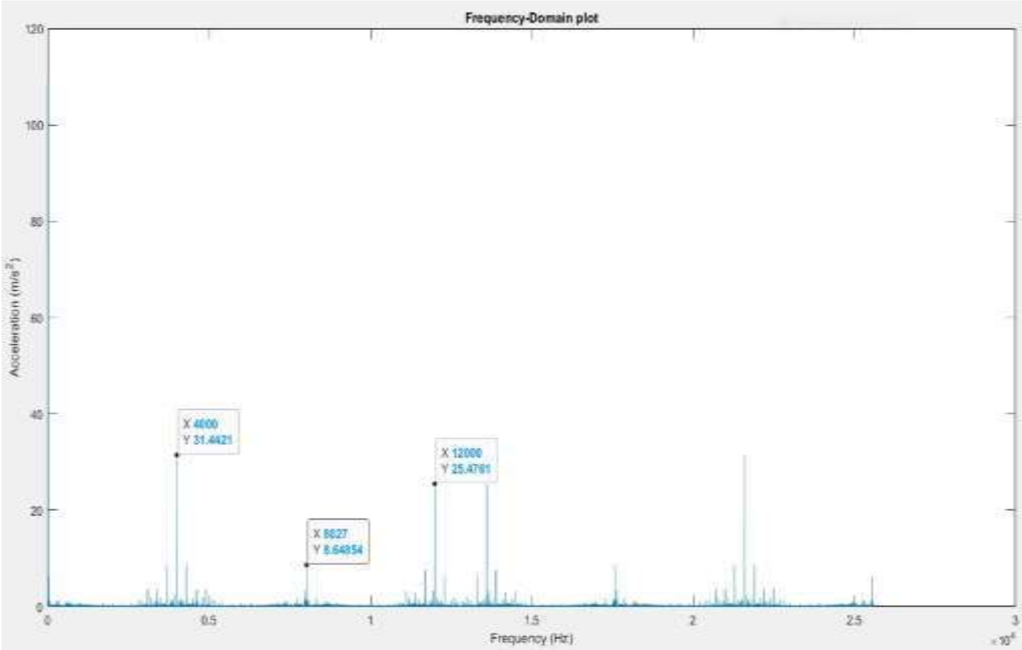

Fig. 4.2(f) Vibration response in frequency domain for load with 50N for 800 hours

From fig. 4.2(f), it can be noticed that the value of acceleration is about 31.4421 m/s² at 800 hours running condition under the load of 50N.

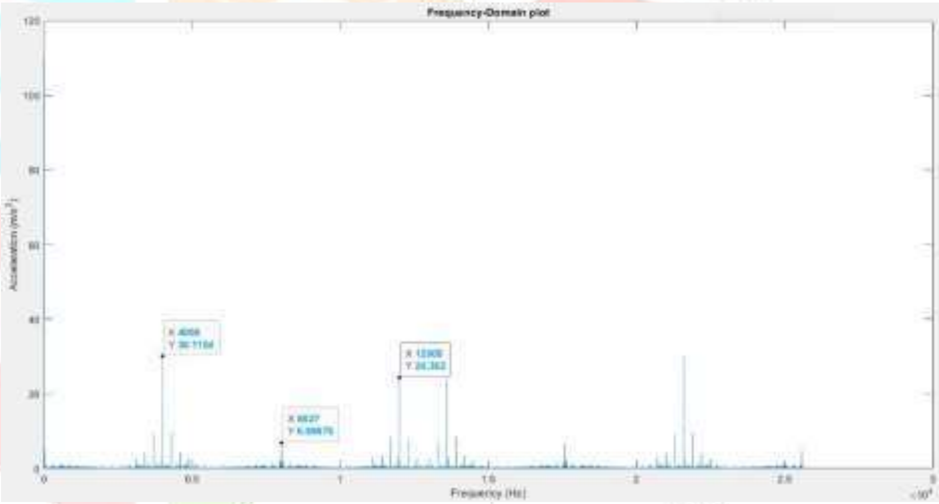

Fig. 4.2(g) Vibration response in frequency domain load with 50N for 900 hours

From fig. 4.2(g), it can be noticed that the value of acceleration is about 30.1154 m/s² at 900 hours running condition under the load of 50N.

Gear mesh frequency (GMF) is a significant factor in gearbox vibrations. The vibration frequency of test gears is shown in Table 4.1. When the gear rotates at 600 rpm, the frequency is 10 Hz, whereas the pinion rotates at 16 Hz. It can be noticed that spectrum plot of gear rotational frequency and its harmonics (1x, 2x, 3x, etc.) few peaks are present in samples for different running time conditions. 9th multiple of the gear mesh frequency (450Hz) shows dominancy over all other harmonics. The peaks of multiples of gear mesh frequency can be noticed by the FFT analysis.

Table 4.1: Characteristic Vibration Frequency of test gears

Parameters	Frequency (Hz)
Gear rotational frequency	10
Pinion rotational frequency	16
Gear mesh frequency	450

From inspecting fig. 4.2(a) and fig. 4.2(b), we can notice that there is change in the acceleration from 300th hour running condition to 400th hour running condition i.e., the value of acceleration has decreased from 22.0598 m/s^2 to 19.1553 m/s^2. We can notice that there is change in the acceleration from 400th hour running condition to 500th hour running condition i.e., the value of acceleration has increased from 19.1553 m/s^2 to 47.1019 m/s^2 in fig. 4.2(b), fig. 4.2(c). The value of acceleration has decreased from 47.1019 m/s^2 to 19.1989 m/s^2 in 500th hour to 700th hour running condition as evident in fig. 4.2(c), 4.2(d) and 4.2(e). The value of acceleration again increases from 19.1989 m/s^2 to 31.4421 m/s^2 as seen in fig. 4.2(e) and fig. 4.2(f). There is a minute decrease of acceleration from 800th to 900th hour i.e., 31.4421 m/s^2 to 30.1154 m/s^2 in fig. 4.2(f) and fig. 4.2(g).

VI. CONCLUSION AND FUTURE

Vibration analysis of gearboxes is a crucial technique used to assess the condition, performance and potential issues in gearbox systems. By analysing the vibrations produced by the gears during operation, engineers can gain valuable insights into the gearbox's health, detect abnormalities and take appropriate maintenance or corrective actions. Viscosity analysis of gearbox oil plays a crucial role in assessing the fluid's flow behaviour and its suitability for lubricating gears within a gearbox. This project presents condition monitoring of the gearbox using signal processing techniques and lubrication regime analysis technique. The experiment was conducted by taking the signals from the test gearbox using an accelerometer for every 100 hours and corresponding oil samples were collected. Acquired signals were studied using the Fast Fourier transform (FFT) technique and the oil samples were analysed based on viscosity and shear rate. Based on the experimental results following conclusions are drawn: The Time-domain plot only depicts the signal's amplitude fluctuating over time which does not provide diagnostic information about the condition of gearbox. The Frequency-domain plot gives necessary information to diagnose the problem in gearbox. As seen from the frequency domain plots, there is a dominant peak at 9th harmonic of gear mesh frequency of about 4000 Hz. Thus proving to be an effective analysis using vibration signals. The oil viscosity analysis provides the information regarding the viscosities that varies with respect to time. From the Lubrication regime analysis, the viscosity of the lubricating oil has increased from 580 mPa.s at no load condition to 1000 mPa.s at the end of 500 hours. This increase in viscosity is due to a combination of factors, including wear debris accumulation. Hence Lubrication oil analysis along with vibration signals can be recommended for condition monitoring of gearbox.

VII. FUTURE SCOPE

The future scope of condition monitoring of gearboxes using oil viscosity analysis is driven by advancements in sensor technology, data analytics, advanced sensor technologies, and intelligent systems.AI and ML algorithms will play a significant role in analysing large volumes of data collected from vibration and oil viscosity sensors. These algorithms will identify patterns, detect anomalies, and predict potential failures, enabling timely maintenance interventions and minimizing downtime. The future of gearbox condition monitoring lies in shifting from reactive maintenance to proactive strategies. Continuous monitoring, data analysis, and trend tracking will facilitate condition monitoring, allowing for timely repairs or component replacements before failures occur.

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