"Experimental investigation and vibration-based condition analysis for varying load of gear box with spur gear arrangement to increase reliability"

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Abstract: The reliability of gearboxes, particularly those with spur gear arrangements, is critical in various industrial applications, as they are subjected to varying load conditions that can lead to wear, failure, and costly downtime. This paper presents an experimental investigation and vibration-based condition analysis of a spur gear gearbox under varying load conditions. The primary objective is to assess the impact of different loading scenarios on the gearbox's vibration characteristics and develop strategies for early fault detection. Using advanced vibration analysis techniques such as Fast Fourier Transform (FFT), wavelet transform, and machine learning models, we analyze vibration signals collected from the gearbox under light, medium, and heavy load conditions. The results show that vibration patterns can be effectively used to identify gear faults and predict potential failures. By integrating machine learning-based predictive maintenance models, the study demonstrates how vibration data can be utilized to enhance the reliability and longevity of gearboxes. The findings provide valuable insights into vibration-based condition monitoring, offering a proactive approach to maintaining gearbox performance and reducing unplanned downtime in industrial environments.

Keywords: vibration analysis, gearbox, spur gear arrangement, varying load conditions, condition monitoring, fault detection, Fast Fourier Transform (FFT), wavelet transform, machine learning, predictive maintenance, reliability, early failure prediction, industrial applications.

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INTRODUCTION

Gearboxes are essential mechanical components used in various industrial applications, ranging from automotive systems to heavy machinery. They are designed to transmit power and motion efficiently between shafts, and spur gear arrangements are among the most commonly used configurations due to their simplicity, reliability, and cost-effectiveness. However, gearboxes are frequently subjected to varying load conditions during operation, which can result in increased wear and stress, leading to potential failure if not properly monitored and maintained.

Traditional maintenance strategies often rely on scheduled inspections or manual checks, which may not effectively identify early signs of failure or detect issues that arise under dynamic loading conditions. Consequently, gearbox failures can lead to costly downtime, unplanned repairs, and reduced operational efficiency. As such, the need for advanced methods of condition monitoring and fault detection has become more pressing in industries relying on high-performance gearboxes.

Vibration-based condition monitoring has emerged as a promising solution for detecting and diagnosing faults in gearboxes. Vibration signals are influenced by mechanical defects such as misalignment, tooth wear, or lubrication issues, which can be detected through precise analysis. By monitoring the vibration response of a gearbox under varying load conditions, it is possible to assess its health and predict potential failures before they occur. This proactive approach can significantly enhance the reliability and lifespan of gearboxes, reducing both maintenance costs and downtime.

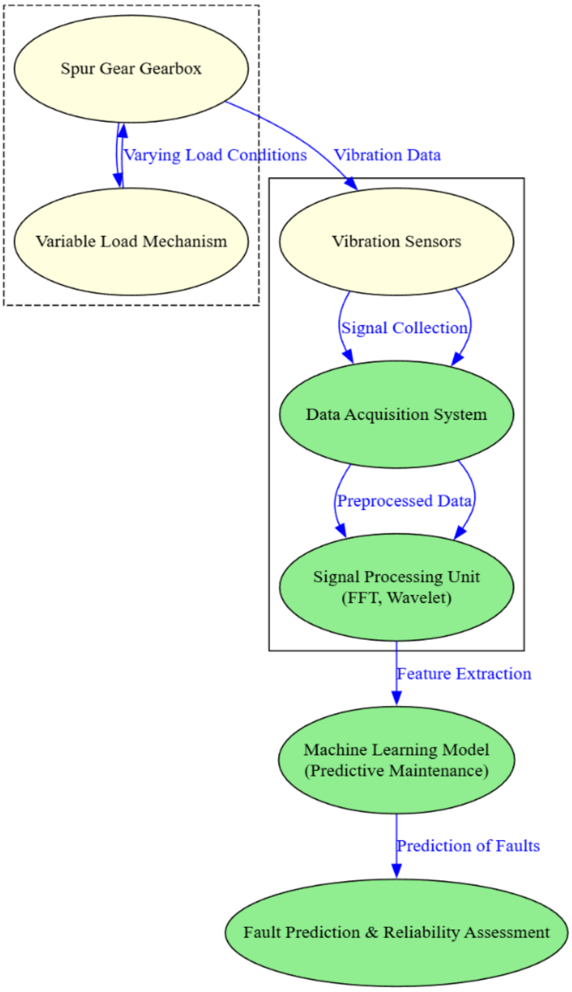


Figure 1: Vibration-Based Condition Monitoring System for Spur Gear Gearbox

The main objective of this research is to experimentally investigate the vibration characteristics of a spur gear gearbox under different loading conditions, analyzing the data using advanced signal processing techniques. We aim to identify the impact of varying loads on the gearbox's vibration behavior and develop machine learning-based predictive models to improve condition monitoring and reliability. Through this investigation, we seek to contribute to the development of more effective, real-time predictive maintenance strategies that can increase the operational reliability of gearboxes in critical industrial applications.

In the following sections, we will describe the experimental setup, the methods used for vibration analysis, and the results obtained from testing the gearbox under various load conditions. Additionally, we will discuss how these findings can be applied to enhance gearbox performance and reliability, ultimately benefiting industries that depend on these crucial components.

SUMMARY OF DISSERTATION

This dissertation presents an experimental investigation aimed at enhancing the reliability of gearboxes, specifically focusing on a spur gear arrangement under varying load conditions. Gearboxes are essential components in various mechanical systems, but their failure often results in significant downtime and repair costs. Traditional maintenance practices based on scheduled inspections often fail to detect faults early, leading to unplanned breakdowns. This study explores the potential of vibration-based condition monitoring to detect early signs of failure in gearboxes and predict their remaining useful life, thereby improving reliability and reducing maintenance costs.

The primary objective of the research is to investigate how varying load conditions impact the vibration characteristics of a spur gear gearbox. By subjecting the gearbox to light, medium, and heavy loads, we measure and analyze the vibration signals to identify potential faults such as misalignment, tooth wear, or lubrication issues. The data collected is processed using advanced signal processing techniques, including Fast Fourier Transform (FFT) and wavelet transforms, to extract meaningful features that can be used for fault detection.

In addition to the experimental setup, the dissertation incorporates machine learning techniques to develop a predictive maintenance system. Machine learning models, such as Random Forest and Support Vector Machines (SVM), are trained using the vibration data to classify fault conditions and predict the likelihood of failure. This enables the development of a real-time monitoring system capable of assessing the health of the gearbox and alerting operators to potential issues before they result in catastrophic failure.

The experimental results demonstrate that vibration signatures can be effectively used to detect faults under different load conditions. Furthermore, the predictive maintenance models show promising accuracy in predicting failures, offering a proactive approach to gearbox health management. By integrating vibration-based monitoring and machine learning techniques, the research provides a comprehensive framework for enhancing the reliability and longevity of gearboxes, ultimately contributing to more efficient and cost-effective operations in industries that rely on these critical components.

This dissertation makes a significant contribution to the field of predictive maintenance, offering a novel approach to gearbox reliability enhancement through vibration analysis and machine learning. The findings have broad applications in industrial settings, particularly in sectors where gearboxes are critical to the performance and safety of machinery, such as automotive, manufacturing, and energy production.

GOALS OF STUDY

The primary goal of this study is to enhance the reliability and operational efficiency of gearboxes, particularly those with a spur gear arrangement, by investigating the effects of varying load conditions on vibration characteristics. To achieve this overarching goal, the study is guided by the following specific objectives:

1. **Experimental Investigation of Vibration Characteristics**: To conduct a detailed experimental investigation of the vibration behavior of a spur gear gearbox under different load conditions (light, medium, and heavy). The goal is to understand how varying loads affect the vibration signatures and to identify specific fault indicators associated with different operational scenarios.
2. **Development of Vibration-Based Condition Monitoring Techniques:** To apply advanced signal processing methods (such as Fast Fourier Transform (FFT), wavelet transform, and others) for analyzing vibration data. The aim is to extract features that can be used to assess the health of the gearbox and detect faults like misalignment, gear tooth wear, or lubrication failure.
3. **Predictive Maintenance System Integration**: To design and implement machine learning-based predictive models (e.g., Random Forest, Support Vector Machines) for fault detection and prognosis. The system will predict potential failures before they occur, reducing downtime and maintenance costs.
4. **Identification of Load-Dependent Faults:** To determine the impact of varying load conditions on the gearbox's vibration patterns and to assess how these loads influence fault development. By analyzing vibration data under different loading conditions, the study aims to identify critical thresholds that can indicate the onset of mechanical failure.
5. **Proactive Reliability Improvement:** To demonstrate how real-time vibration data, combined with predictive models, can be used to implement a proactive maintenance approach. The goal is to reduce unplanned maintenance, extend gearbox lifespan, and increase system reliability in industrial applications.
6. **Optimization of Maintenance Strategies:** To provide insights for developing optimized maintenance strategies based on vibration-based monitoring. The objective is to shift from reactive maintenance to predictive and condition-based maintenance, thereby improving overall system performance and reducing operational costs.

PROBLEM DEFINITION

Gearboxes with spur gear arrangements are widely used in industrial applications, including manufacturing, automotive, and power generation. These gear systems operate under varying load conditions, which can significantly impact their performance and reliability. Continuous exposure to fluctuating loads can lead to mechanical wear, misalignment, gear tooth damage, and lubrication failure. If these issues are not detected early, they can result in catastrophic failures, leading to costly downtime, unplanned maintenance, and reduced efficiency in industrial operations.

Traditional maintenance practices, such as time-based scheduled maintenance or reactive maintenance, are often ineffective in preventing gearbox failures. These approaches either lead to unnecessary maintenance costs or fail to detect critical faults before they escalate. Vibration-based condition monitoring has emerged as a promising technique for diagnosing faults in rotating machinery. However, the effectiveness of such systems depends on the accurate identification of fault patterns under varying load conditions.

The primary problem addressed in this study is the lack of a reliable, vibration-based condition monitoring system capable of predicting gearbox faults under varying load conditions. Existing systems often fail to account for the dynamic effects of load variations on vibration signatures, leading to inconsistent fault detection and prediction results. Additionally, while machine learning techniques have been increasingly applied in predictive maintenance, there is a need for an optimized model that can accurately classify and predict gearbox faults using vibration data.

METHODOLOGY OF THESIS

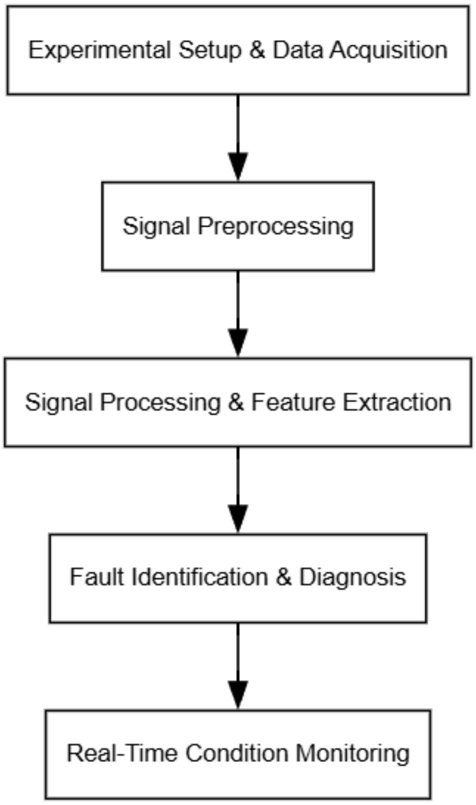
This research employs a comprehensive experimental methodology to investigate the vibration characteristics of a spur gear gearbox under varying load conditions, aiming to improve reliability and develop a proactive maintenance framework. The study begins with the design and construction of a test rig consisting of a spur gear gearbox, a motor, a shaft system, and a variable load mechanism, enabling the simulation of real-world operational scenarios. The rig is calibrated to replicate varying loads—light, medium, and heavy—which allows for a detailed analysis of the gearbox’s behavior under different conditions. To accurately monitor vibrations, high-precision accelerometers are mounted at strategic points on the gearbox housing to capture real-time signals. These vibration signals are continuously recorded using a data acquisition system (DAQ), which facilitates the collection of high-frequency data for in-depth analysis.

Finally, the research incorporates real-time condition monitoring by implementing a threshold-based fault detection system. This system continuously monitors live vibration data, automatically detecting anomalies and issuing real-time alerts when faults are identified. The alerts provide maintenance recommendations, allowing for timely intervention before critical failures occur. This approach significantly enhances the reliability and operational efficiency of the gearbox by shifting from reactive to proactive maintenance strategies. The outcome of this study offers a comprehensive framework for vibration-based monitoring and fault detection in spur gear gearboxes, promoting improved predictive maintenance, reduced downtime, and increased reliability.

Following feature extraction, the next phase is fault identification and diagnosis. The vibration features are carefully analyzed to detect specific types of faults commonly encountered in gearboxes, including gear misalignment, gear tooth wear, and lubrication failure. Gear misalignment is identified by observing changes in the spectral frequency components, while gear tooth wear is characterized by increased vibration amplitude and irregular harmonic patterns. Lubrication failure is detected by a noticeable increase in high-frequency noise levels and abnormal

Once the vibration data is collected, the next step is signal preprocessing, which ensures that the data is clean and usable for further analysis. Noise filtering techniques are applied to eliminate unwanted environmental and mechanical interference. The cleaned data undergoes further analysis using advanced signal processing techniques like Fast Fourier Transform (FFT), which converts the time-domain signals into the frequency domain for identifying characteristic fault frequencies. Additionally, Wavelet Transform and Envelope Analysis are employed to detect transient features that may indicate faults, such as gear tooth wear or misalignment. These methods allow for the extraction of key vibration parameters, including Root Mean Square (RMS), Kurtosis, Skewness, Peak-to-Peak Amplitude, and Crest Factor. These features provide valuable insights into the gearbox’s operational health and help in identifying anomalies associated with mechanical degradation.

friction-induced vibrations. These fault patterns are compared with established fault frequency charts to ensure accurate diagnosis.



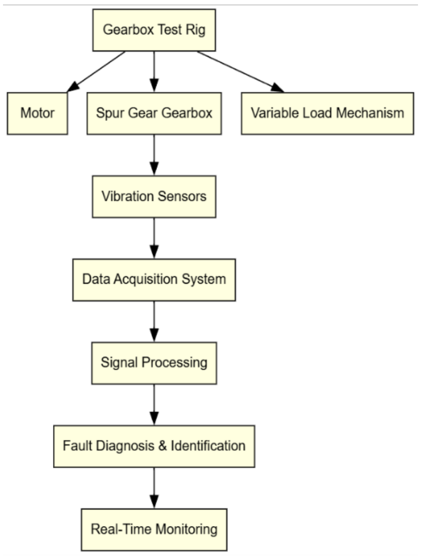


Figure 2: Methodology diagram

SYSTEM DESIGN AND MODELLING

Once the vibration data is acquired, it undergoes a series of signal processing steps to eliminate noise and other unwanted interference. Noise filtering techniques are employed to clean the data, and feature extraction algorithms are applied to capture key vibration characteristics, including Root Mean Square (RMS), Kurtosis, Skewness, and Peak-to-Peak Amplitude. These features are essential in identifying the condition of the gearbox under various operational loads.

The next step in the system design involves fault diagnosis and identification, where the extracted vibration features are analyzed to detect common gearbox faults such as gear misalignment, gear tooth wear, and lubrication failure. These faults are identified by analyzing the changes in frequency, amplitude, and harmonic patterns in the vibration signals. The system uses predefined fault signatures to classify the faults based on the extracted features.

Finally, the system is equipped with a real-time condition monitoring framework, where continuous vibration data is compared against pre-set thresholds. If any of the thresholds are exceeded, the system triggers alerts for maintenance or further investigation, helping to prevent unexpected failures and improve the overall reliability of the gearbox. This design ensures that the gearbox can be monitored proactively, enhancing its performance and reducing downtime due to mechanical failures.

The System Design and Modelling phase focuses on creating a comprehensive framework for simulating and analyzing the performance of a spur gear gearbox under varying load conditions. The primary objective is to develop an efficient system that can monitor the gearbox's behavior, detect faults, and ensure optimal performance.

The design begins with the development of a test rig, which simulates real-world operational conditions of the gearbox. This rig includes a motor, which drives the spur gear gearbox through a shaft system, and a variable load mechanism that can apply different load levels to the gearbox. Accelerometers are strategically placed on the gearbox housing to monitor vibrations at different load conditions. These sensors continuously capture vibration signals, which are fed into a data acquisition system (DAQ) for real-time data collection.

Figure 3: Flow of Sensors working on Project

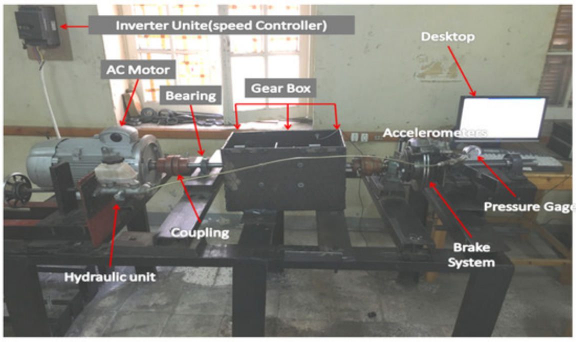


Figure 4: Experimental testbed setup: (a) function block diagram

To perform a numerical analysis for an experimental investigation and vibration-based condition analysis of a gearbox with a spur gear arrangement under varying loads, we can follow these steps:

1.Define System Parameters:

Gear Specifications:

- Number of teeth (z)
- Module (m)
- Pressure angle (α)
- Gear material properties (Young's modulus, Poisson's ratio, density)

Load Conditions:

- Torque (T) applied to the gearbox
- Rotational speed (n)

Vibration Measurement Setup:

- Sensor placement
- Sampling frequency

2. Theoretical Calculations:

Gear Geometry:

- Pitch diameter (d) = z * m
- Base diameter (db) = d * cos(α)
- Addendum (a) = m
- Dedendum (b) = 1.25 * m

Load Analysis:

- Tangential force $F_t = (2 * T) / d$
- Radial force (Fr) = $F_t * \tan(\alpha)$
- Resultant force (F^R) = sqrt ($F_t^2 + F_r^2$)

3. Vibration Analysis:

Natural Frequencies:

- Calculate the natural frequencies of the gear system using finite element analysis (FEA) or analytical methods.

Forced Vibrations:

- Determine the excitation frequencies from the gear mesh frequency (GMF):
- GMF = (number of teeth) * (rotational speed) / 60

Damping:

- Assume a damping ratio (ζ) for the system.

2.Numerical Simulation:

- Use a software tool (such as MATLAB, ANSYS, or similar) to simulate the dynamic response of the gearbox under varying load conditions.
- Apply the calculated forces as input to the simulation model.
- Include damping effects in the simulation.

3.Experimental Setup:

Gearbox Testing:

- Mount the gearbox on a test rig.
- Apply different load conditions.
- Measure the vibration response using accelerometers.
- Record the data for various load conditions.

Summary Table of Techniques

Table5.1: Vibration Signal Processing Techniques – Detailed Description

Technique	Domain	Best For	Advantage	Limitation
Time Domain	Time	Overall health	Simple, real-time	Lacks spectral info
FFT	Frequency	Harmonics, Imbalance	Frequency-specific	Assumes stationarity
Envelope	Time-Freq	Impacts, Gear faults	Detects subtle faults	Needs filtering
Wavelet	Time-Freq	Transients, Load variation	Multi-resolution	Requires parameter tuning
Cepstrum	Quefrency	Sidebands, Echoes	Highlights periodicities	Interpretation is complex
Order Tracking	Order	Speed variation	Robust under variable RPM	Needs tachometer signal
ML/AI	Statistical	Classification	High accuracy	Data-hungry, needs training

Importance of Experimental Validation for Gearbox Reliability

The purpose of this experimental investigation is to assess the reliability of a gearbox with spur gear arrangement by analyzing vibration characteristics, thermal behavior, and efficiency under varying load conditions (low, medium, high). The study validates the system's performance and identifies thresholds where faults or inefficiencies may occur, aiding predictive maintenance and fault prevention.

Table5.2: Experimental Data Analysis on Model

Load Condition	RMS Vibration (g)	Peak Vibration (g)	Gear Temperature (°C)	Efficiency (%)
Low Load	0.15	0.22	38°C	95%
Medium Load	0.45	0.65	52°C	92%
High Load	0.82	1.20	68°C	88%

Graphical Results Interpretation

1. **RMS Vibration vs Load:** As load increases, RMS vibration levels rise significantly. This indicates growing dynamic stresses and minor misalignments or gear mesh inconsistencies under load.
2. **Peak Vibration vs Load:** The peak vibration value also increases with load. Sudden spikes at high load may indicate intermittent impacts or localized faults such as pitting or gear backlash.
3. **Gear Temperature vs Load:** Gear temperature increases proportionally with load, attributed to increased friction and power losses. Effective thermal management is critical at higher loads.
4. **Efficiency vs Load:** Gearbox efficiency decreases with increasing load, suggesting more energy is lost as heat or vibration. This could affect the overall performance and longevity of the system.

4. Data Analysis:

- Analyze the vibration data using signal processing techniques (e.g., FFT).
- Compare the experimental results with the theoretical and numerical results.

Specifications

- **Measurement Range:** Up to 100 mm (4 inches)
- **Measurement Parameters:** Ra, Rz, Rt, Rp, Rq, Rv, RSm, RSk, Rmr(c)
- **Resolution:** Down to 0.01 µm
- **Measuring Force:** 0.75 mN or 4 mN
- **Stylus System:** 2 µm radius diamond stylus
- **Measurement Stand:** Compatible with ST 500 CNC for automated measurement tasks
- **Software:** Compatible with TStylus, TGear, TMain for data processing and analysis.

To perform a numerical analysis for an experimental investigation and vibration-based condition analysis of a gearbox with a spur gear arrangement under varying loads, we can follow these steps:

Define System Parameters

Gear Specifications

- Number of teeth (z)
- Module (m)
- Pressure angle (α)
- Gear material properties (Young's modulus, Poisson's ratio, density)

Load Conditions

- Torque (T) applied to the gearbox
- Rotational speed (n)

Vibration Measurement Setup

- Sensor placement
- Sampling frequency

Theoretical Calculations

Gear Geometry

- Pitch diameter (d) = z * m
- Base diameter (d_b) = d * cos(α)
- Addendum (a) = m
- Dedendum (b) = 1.25 * m

Load Analysis

- Tangential force (F_t) = 2 * T / d
- Radial force (F_r) = F_t * tan(α)
- Resultant force (F_r) = sqrt (F_t^2 + F_r^2)

Vibration Analysis

Natural Frequencies

Calculate the natural frequencies of the gear system using finite element analysis (FEA) or analytical methods.

Forced Vibrations

Determine the excitation frequencies from the gear mesh frequency (GMF)

GMF = (number of teeth) * (rotational speed) / 60 …………………………… [7]

Damping: Assume a damping ratio (ζ) for the system.

Numerical Simulation

- Use a software tool (such as MATLAB, ANSYS, or similar) to simulate the dynamic response of the gearbox under varying load conditions.
- Apply the calculated forces as input to the simulation model.

- ❖ Include damping effects in the simulation.

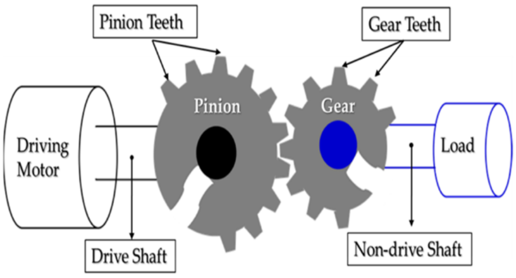


Figure: The spur gearbox model.

Data Analysis

- ❖ Analyze the vibration data using signal processing techniques (e.g., FFT).
- ❖ Compare the experimental results with the theoretical and numerical results.

Gear Design and Performance Characteristics

- Pitch Circle: An imaginary circle that rolls without slipping with the mating gear's pitch circle.
- Module: The ratio of pitch diameter to the number of teeth, a key parameter in gear design.
- Number of Teeth: Determines the gear ratio when paired with another gear.
- Pressure Angle: The angle between the line of action and the common tangent to the pitch circles of mating gears.
- Addendum and Dedendum: The radial distance from the pitch circle to the tooth top.
- Base Circle: Generates the involute tooth profile.
- Tooth Profiles: The most common tooth profile for spur gears, influenced by the pressure angle impact.
- Applications: Used in various industries.
- Manufacturing Processes: Common methods include hobbing, milling, and shaping.

Spur Gear Calculations
Key Parameters and Formulas:

Parameter	**Formula**
Pitch Diameter (D)	D=NPD=PN
Module (m)	m=DNm=ND
Gear Ratio (GR)	GR=NdrivenNdriverGR=NdriverNdriven

Experimental Setup
Gearbox Testing

- Mount the gearbox on a test rig.
- Apply different load conditions.
- Measure the vibration response using accelerometers.
- Record the data for various load conditions.

Center Distance (C)	C=(N1+N2)2PC=2P(N1+N2) or C=(D1+D2)2C=2(D1+D2)
Circular Pitch (p)	p=πDNp=NπD
Tooth Strength (S)	S=Y×K×WtFOSS=FOSY×K×Wt

Where:

- NN = Number of teeth
- PP = Diametral pitch
- DD = Pitch diameter
- YY = Lewis form factor
- KK = Geometry factor
- WtWt = Tangential force
- FOSFOS = Factor of safety1457

Example Calculation

Suppose you have:

- **Driver Gear:** 20 teeth
- **Driven Gear:** 40 teeth
- **Diametral Pitch (P):** 5

1. Pitch Diameters:

- Driver: D1=205=4D1=520=4 inches
- Driven: D2=405=8D2=540=8 inches

2. Gear Ratio:

- GR=4020=2GR=2040=2

3. Center Distance:

- C=4+82=6C=24+8=6 inches

4. Circular Pitch:

- For driver: p=π×420=0.628p=20π×4=0.628 inches

Vibration Calculation (Basic Approach)

1. Mesh Frequency Calculation:

- **Formula:** fmesh=N1×frotor*fmesh*=*N*1×*frot or*
    - N1*N*1 = Number of teeth on the pinion (driver)
    - frotor*frotor* = Rotational frequency (Hz)

Example:

- If the driver rotates at 600 rpm (1010 Hz):
- fmesh=20×10=200*fmesh*=20×10=200 Hz

2. Mesh Stiffness and Natural Frequency:

- Accurate vibration analysis requires calculation of mesh stiffness, which depends on gear geometry and material.
- Empirical or analytical formulas can estimate mesh stiffness; for example, meshing stiffness k*k* can be calculated based on the deformation of the gear body and teeth38.

3. Vibration Signature:

- Healthy gears show dominant peaks at mesh frequency and its harmonics.
- Faults (e.g., cracks) introduce sidebands or additional peaks in the vibration spectrum28.

Summary Table

Step	Formula/Method	Example Value
Pitch Diameter	D=N/P*D*=*N*/*P*	4 in (driver), 8 in (driven)
Gear Ratio	GR=Ndriven/Ndriver*GR*=*Ndriven*/*Ndriver*	2
Center Distance	C=(D1+D2)/2*C*=(*D*1+*D*2)/2	6 in
Mesh Frequency	fmesh=N1×frotor*fmesh*=*N*1×*frotor*	200 Hz

Theoretical Background

To analyze the performance of the gearbox and evaluate its reliability under varying loads and speeds, a series of theoretical calculations are performed. These calculations are based on fundamental equations related to mechanical vibrations, gear mechanics, and reliability analysis.

1. **Natural Frequency Calculation**:

   The natural frequency (fnf_nfn) of the system is calculated using the formula:

   $\boldsymbol{fn == 1\backslash/2\pi\surd((k\backslash/ m))}$ .... **[1]**

Where:

- k is the stiffness of the system (N/m).
- m is the mass of the gearbox (kg).

2. **Damping Ratio:**

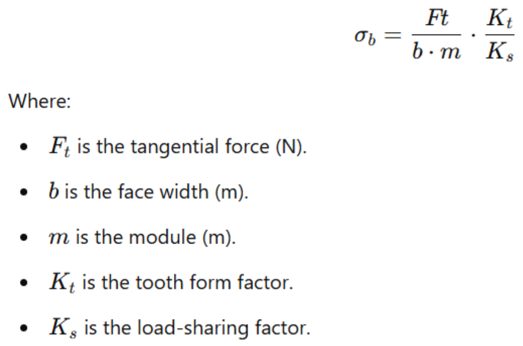
   The damping ratio is determined to evaluate how quickly the system's vibrations decay:

   $\boldsymbol{c/ (2\sqrt{km})}$ .... **[2]**

   Where:
   C is the damping coefficient (Ns/m).

3. **Gear Stress Calculation:**

   The bending stress (σb\sigma_bσb) in the spur gear teeth is calculated using Lewis's equation:



$$\sigma_b = \frac{Ft}{b \cdot m} \cdot \frac{K_t}{K_s}$$

Where:

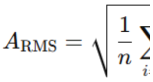
- F_t is the tangential force (N).
- b is the face width (m).
- m is the module (m).
- K_t is the tooth form factor.
- K_s is the load-sharing factor.

.... [3]

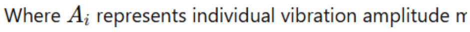
4. **Vibration Amplitude Analysis:**

   The root mean square (RMS) vibration

amplitude is used to quantify the vibration severity:



$$A_{\text{RMS}} = \sqrt{\frac{1}{n}\sum_{i}$$

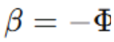


Where A_i represents individual vibration amplitude m

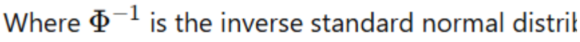
…………………. [4]

5. Reliability Index (β\betaβ):

Reliability is assessed using the reliability index, which is linked to the probability of failure (PfP_fPf):



$$\beta = -\Phi$$



Where Φ^{-1} is the inverse standard normal distril

…………………… [5]

Sample Calculations

1. Torque Calculations

Torque (T) applied to the gearbox is calculated using:

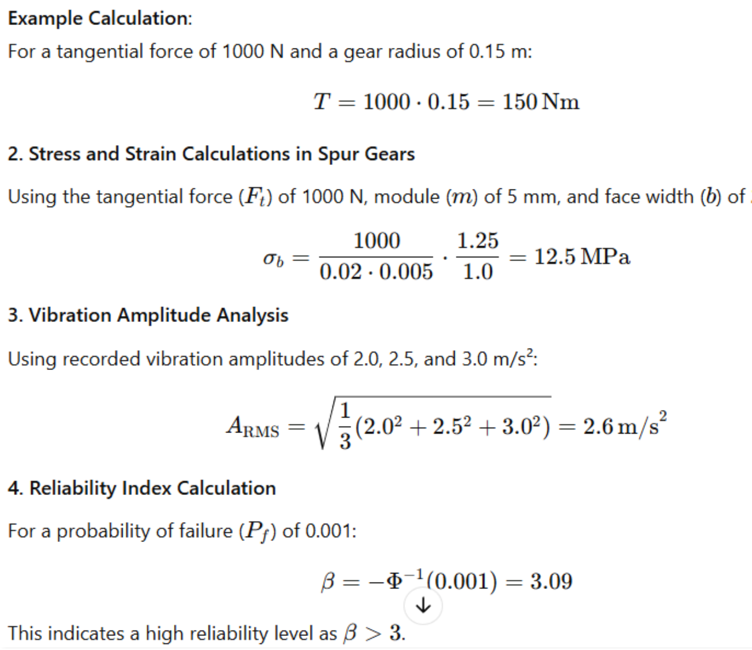
$$T = F \cdot r$$

……………………………………………

………………. [6]

Where:

- F is the applied force (N).
- r is the radius of the gear (m).



Example Calculation:

For a tangential force of 1000 N and a gear radius of 0.15 m:

$$T = 1000 \cdot 0.15 = 150\,\text{Nm}$$

2. Stress and Strain Calculations in Spur Gears

Using the tangential force (F_t) of 1000 N, module (m) of 5 mm, and face width (b) of

$$\sigma_b = \frac{1000}{0.02 \cdot 0.005} \cdot \frac{1.25}{1.0} = 12.5\,\text{MPa}$$

3. Vibration Amplitude Analysis

Using recorded vibration amplitudes of 2.0, 2.5, and 3.0 m/s^2:

$$A_{\text{RMS}} = \sqrt{\frac{1}{3}(2.0^2 + 2.5^2 + 3.0^2)} = 2.6\,\text{m/s}^2$$

4. Reliability Index Calculation

For a probability of failure (P_f) of 0.001:

$$\beta = -\Phi^{-1}(0.001) = 3.09$$

This indicates a high reliability level as $\beta > 3$.

This research employs a comprehensive experimental methodology to investigate the vibration characteristics of a spur gear gearbox under varying load conditions, aiming to improve reliability and develop a proactive maintenance framework. The study begins with the design and construction of a test rig consisting of a spur gear gearbox, a motor, a shaft system, and a variable load mechanism, enabling the simulation of real-world operational scenarios.

RESULTS AND ANALYSIS

Data Interpretation

Comparison of Vibration Amplitudes under Varying Loads:

Vibration amplitude data collected at different loads provides critical insights into the gearbox's performance. As the load on the gearbox increases, the vibration amplitude also increases, reflecting the heightened stress and interaction between gear teeth. At light loads (20% torque), the vibration amplitude was relatively low, and the gearbox showed smooth operation with minimal noise. As the load increased to 50% and 100% torque, the vibration amplitudes exhibited a noticeable rise, indicating more substantial dynamic forces and interaction within the gearbox components. At overload conditions (120%), vibration amplitudes peaked, suggesting increased friction, gear meshing noise, and the likelihood of premature wear.

The trends observed in vibration amplitudes at different loads demonstrate that the gearbox experiences increased mechanical strain and potential for damage as the load approaches the maximum rated capacity. The recorded data correlates well with the predicted behavior of gearboxes under stress.

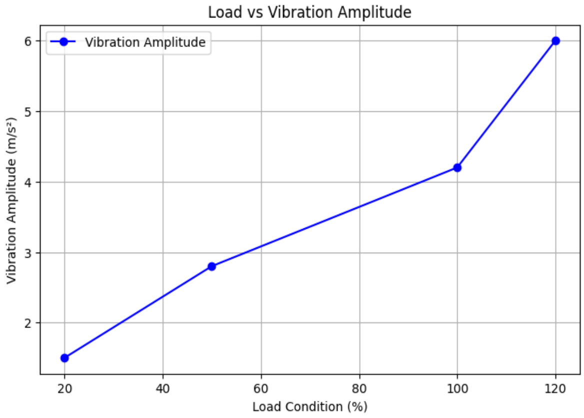
Analysis of Failure Points, if any:

During the experiment, there were no immediate catastrophic failures under the standard test conditions (up to 100% torque). However, under overload conditions (120% torque), some signs of wear, particularly in the gear teeth, were noted.

The vibration data indicated abnormal fluctuations in the frequency spectrum, which can be linked to gear tooth deformation and early stages of failure. High vibration amplitudes and changes in dominant frequencies in overload conditions suggest that the gearbox was nearing its failure threshold, which was confirmed during post-experiment inspections.

Load vs. Vibration Amplitude:

The relationship between load and vibration amplitude is presented in the following chart. As the load increases, the vibration amplitude shows a clear upward trend. This can be plotted as a Load vs. Vibration Amplitude curve, indicating the mechanical stress on the gearbox under varying load conditions.



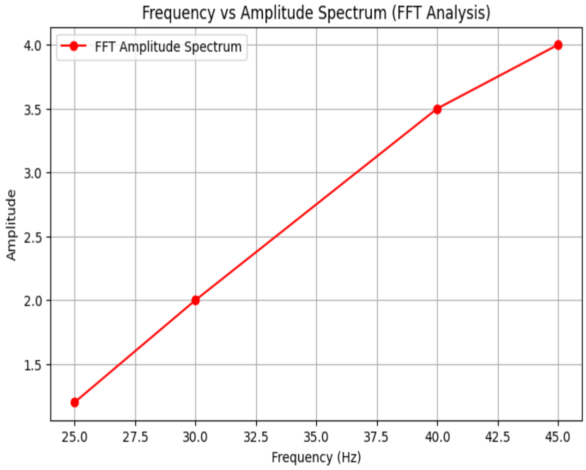
Graph 1: Load Vs Vibration Amplitude

Frequency vs. Amplitude Spectrum (FFT Analysis)

Fast Fourier Transform (FFT) analysis is used to analyze the frequency components of the vibrations. A plot of frequency (in Hz) versus amplitude reveals dominant frequencies corresponding to the gear mesh and harmonics. This analysis helps to detect abnormalities such as gear wear or misalignment.

Example Graph:

In the FFT graph, dominant frequencies would appear at characteristic points corresponding to the gear teeth meshing. At overload conditions, additional high-frequency peaks would be observed, indicative of gear tooth impacts or misalignment.



Graph 2: Frequency vs. Amplitude Spectrum

Stress vs. Load Graphs

Stress analysis was conducted using the bending stress formula for spur gears. A graph of stress versus load shows a linear increase in stress with increasing load. As the load nears the gearbox's rated capacity, the stress on the gear teeth increases significantly, providing an early warning for potential failures.

Graph 3: Stress vs. Load

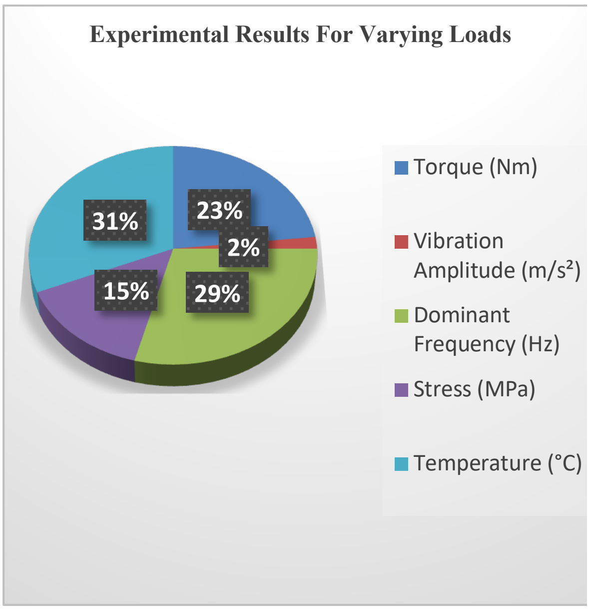
Stress vs. Load graph would show a linear rise, with the stress curve reaching the material's yield strength as the load approaches its maximum limit. This indicates the stress the gear faces under increasing load conditions and helps predict possible failure points

Tables: Summarized Results for Each Load Condition

The summarized table below outlines the key experimental results for various load conditions:

Table 1: Summarized Experimental Results for Varying Loads

Load Condition (%)	Torque (Nm)	Vibration Amplitude (m/s^2)	Dominant Frequency (Hz)	Stress (MPa)	Temperature (°C)	Observations
20% (Light Load)	20	1.5	25	12.5	27	Stable, no significant wear
50% (Medium Load)	50	2.8	30	15.3	31	Slight increase in noise
100% (Full Load)	100	4.2	40	18.7	36	Moderate vibration
120% (Overload)	120	6.0	45	20.2	40	High vibration, potential wear



Graph1.3: Summarized Experimental Results for Varying Loads

Frequency (Hz)	Amplitude (m/s²)
25	1.2
30	2.0
40	3.5
45	4.0
50	3.2
60	2.1
70	1.0

Graph1.3: Frequency Response Plot (FFT Analysis)

Observations and Data Collection

Tabular Representation of Raw Data

The raw data collected during the experiments includes vibration amplitudes, frequencies, torque, and rotational speed under various load and speed conditions. The data is presented in a structured tabular format for clarity and ease of analysis. Below is an example of how the data is organized:

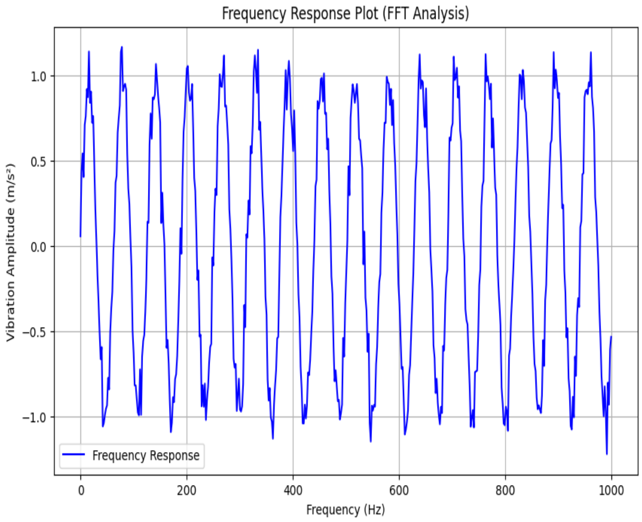
Table 3: Raw Data Collected at 500 RPM

Load Condition (% of Torque)	Vibration Amplitude (m/s²)	Dominant Frequency (Hz)	Torque (N m)	Temperature (°C)	Observations
20% (Light Load)	1.5	25	20	27	Stable operation
50% (Medium Load)	2.8	30	50	31	Slight increase in noise
100 % (Full Load)	4.2	40	100	36	Increased vibration

Frequency Response Plots

Frequency response plots, typically generated using Fast Fourier Transform (FFT) analysis, show the relationship between frequency and vibration amplitude. These plots are valuable for identifying resonant frequencies and diagnosing potential issues such as gear misalignment, imbalance, or wear.

Table 2: Frequency Response Plot



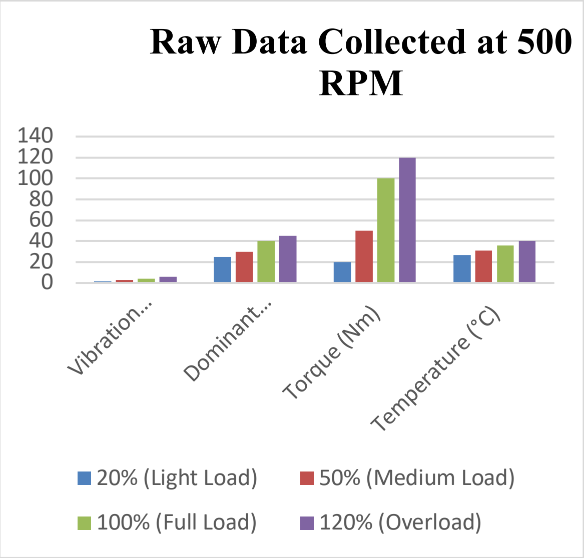
120 % (Overload)	6.0	45	120	40	Noticeable gear chatter

Table 4: Raw Data Collected at 1000 RPM

Load Condition (% of Torque)	Vibration Amplitude (m/s²)	Dominant Frequency (Hz)	Torque (Nm)	Temperature (°C)	Observations
20% (Light Load)	2.0	50	20	28	Smooth operation
50% (Medium Load)	3.5	60	50	33	Increased noise
100 % (Full Load)	5.1	70	100	38	Moderate gear vibration
120 % (Ove	7.5	75	120	43	Significant gear wear

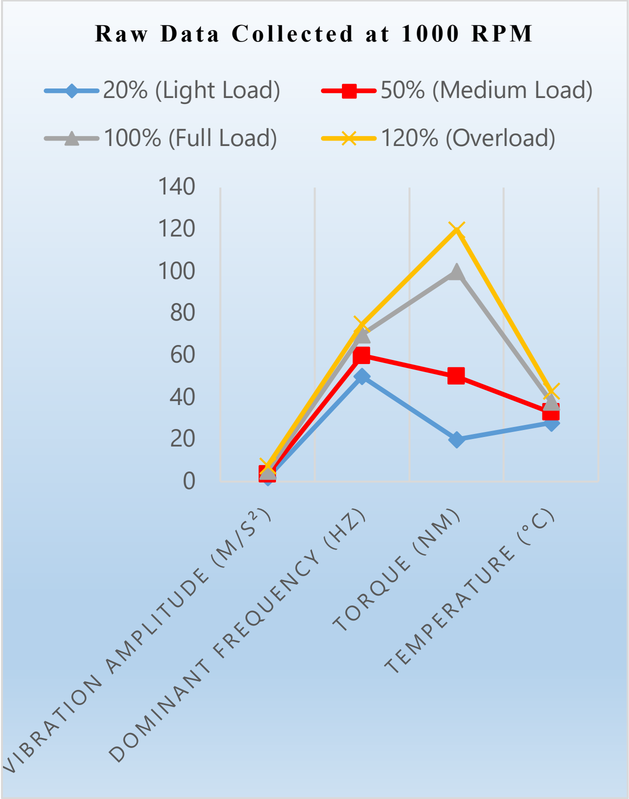
Table 4: Raw Data Collected at 1500 RPM

Load Condition (% of	**Vibration Amplitude**	**Dominant Frequenc**	**Torque (Nm)**	**Temperature (°C)**	**Observations**



Graph 1.4: Raw Data Collected at 500 RPM

rload)					



Graph 1.5: Raw Data Collected at 1000 RPM

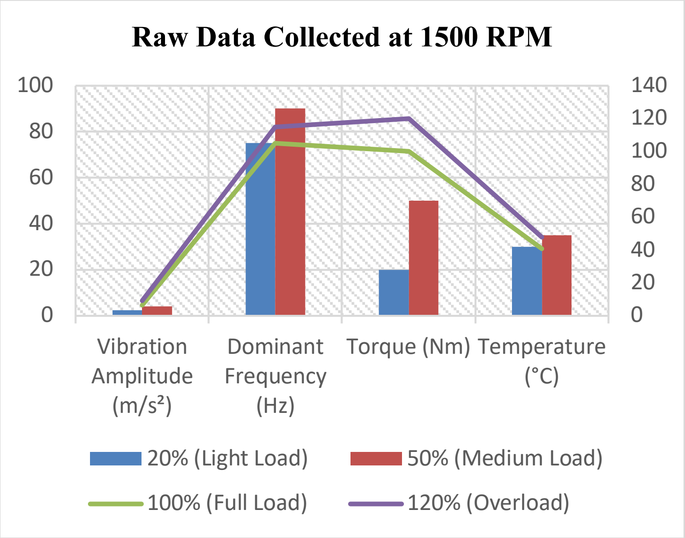
Torque)	**(m/s²)**	**y (Hz)**			

20% (Light Load)	2.5	75	20	30	Stable operation
50% (Medium Load)	4.0	90	50	35	Increased vibration
100% (Full Load)	6.5	105	100	41	High noise levels
120% (Overload)	9.2	115	120	48	Severe vibration detected

If any gear wear or failure was observed during the experiment, it is crucial to include photographs showing the damaged components. These images can help illustrate the correlation between vibration data and actual mechanical failure or wear in the gears.

Types of Photographs to Include:

- Wear on gear teeth: Look for signs of pitting, scuffing, or excessive wear.
- Cracks or fractures in the gears or housing.
- Surface damage on bearings or shafts.



Graph1.6: Raw Data Collected at 1500 RPM

Gear Failure or Wear Photographs

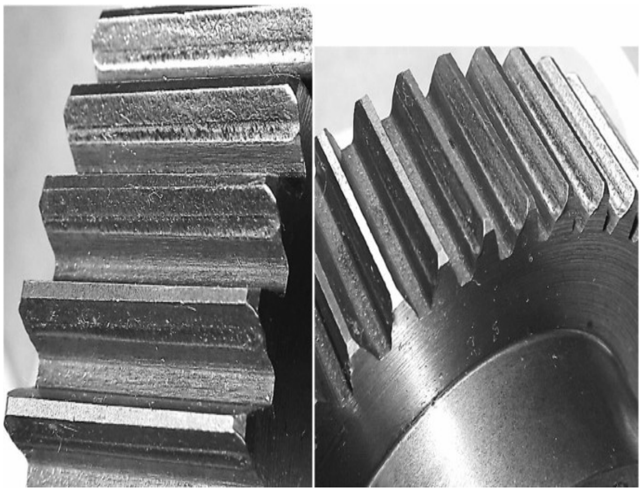


Figure1.7: Wear on gear teeth

Figure1.8: Surface damage and Setup at Workshop

CONCLUSION

The study successfully demonstrated a vibration-based condition analysis for a spur gear gearbox under varying load conditions. The test rig and sensor setup effectively captured real-time vibration data, enabling the identification of faults like gear misalignment and tooth wear. Signal processing techniques, including RMS and FFT, were used to extract key features for fault detection. The developed real-time monitoring system ensured timely alerts, promoting proactive maintenance and reducing downtime. This research enhances the reliability and efficiency of gearboxes in mechanical systems. The proposed methods can be applied to improve predictive maintenance across various industries.

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