Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Computational-Experimental Analysis of Gear Wheel Behavior with Defects under Static Conditions

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This study investigates the structural and dynamic behavior of gear wheels with defects under static conditions, emphasizing defect-induced changes in performance and failure prediction. A computational-experimental methodology was adopted, combining 3D CAD modeling, Finite Element Method (FEM) simulations, and experimental validation to analyze the effects of wear, broken teeth, and root wear on gears. Structural analysis revealed that wear reduces deformation but increases stress concentrations, leading to higher risk of fatigue and failure. Modal analysis showed that defects lower natural frequencies, making gears more flexible and prone to resonance at lower operating speeds, potentially causing mechanical failures. Harmonic analysis revealed complex trends, with displacement and velocity amplitudes generally decreasing with wear, while higher vibrational modes exhibited increased acceleration amplitudes, indicating sensitivity to high-frequency excitations. Broken teeth significantly degrade the structural integrity and dynamic response, with stress concentrations rising and natural frequencies dropping as the number of broken teeth increases. Root wear similarly affects performance, decreasing stiffness and altering modal and harmonic behavior. These findings underline the importance of early detection and monitoring of gear defects to mitigate risks, optimize performance, and enhance gear lifespan. The insights gained from this analysis are critical for predictive maintenance and improving reliability in industrial applications. By integrating numerical and experimental approaches, this research advances our understanding of gear wheel defects and provides a robust framework for their assessment under static conditions.

Keywords: Gear defects, Static conditions, Structural analysis, Finite Element Method (FEM)Predictive maintenance.

1. Introduction

Gears are basic assemblies in the macro-machines and are singularly vital in the conversion of power and movement between the rotating shafts. And, in fact, their range of application is very impressive: from a simple application in households to various industrial equipment, which highlights the significance of these coupes in present-day society. In industrial applications gear systems are used in operation of heavy machineries, manufacturing industries and transport systems by providing and controlling torque, speed of rotation and direction[1]. In countless systems, gears are the parts that determine how well many machines run and operate hence designing or even maintaining gears is a key factor. Gears play their role through engagement of teeth found on at least two elements to allow for the passing of movement as well as the moment generated between them. This ostensibly simple form of mechanism is the fundamental structure behind a host of sectors, ranging from power generation to the fabrication of quality products. These are some of the important applications: torque transmitting, speed variation, reversing of direction, distributing power, and creating mechanical advantage[2]. Gears engage one or more rotating shafts, transmitting power from a driving source to a load,power is smoothly prescribed in an efficient manner dependent upon the demands of specific stretches of application. For instance in automobile engines and industrial turbines; utilization of gears in transmitting torque is used to operate these systems under different circumstances. Similarly, their flexibility in terms of speed this is important because gears enable machines to run at an appropriate speed for given workloads[3]. Whether it is the case of slowing down the driven gear for greater torque or a case of speeding up the same for enhanced rates the level of accuracy provided by gears cannot be rivalled. This feature is very useful in conveyor belts, escalators and wind mill where specific speed and torque output is necessary to run the equipment without breakdown[4].. However, gears play a crucial role in changing the direction of the motion; for instance, spur and bevel gears are the best examples of mechanisms used in changing the motion direction. This functionality can be interface for complex mechanical structure in many applications and especially in cases where micro motion control is a requirement like differential drives in car or rotary angle in factory tools. Furthermore, the power distribution feature of gears also make it possible to distribute energy from a single power source to the many components, an idea common among giant machines such as the textile loom or the food processing machine where several operations must take place at once. In addition to these utilitarian purposes, gears also provide the system with mechanical advantages in that force can be increased with carefully chosen gear ratios, so that machines which have to carry heavy loads, or operate with minimal energy can do so more easily. Due to this, gears are a requirement in mining, construction, and agriculture industries since these machines cannot afford breakdowns[5].

Variations of spur gears, helical gears, bevel gears, and worm gears are other supporting concepts as to their flexibility in regard to the mechanical requirements. Each is specially engineered to provide a certain aspect in performance, speed, sound, or directionality and they are used in applications as diverse as electric drills to elevators. The use of gears in power transmission plays a crucial part thereby providing skeletal support to the machinery through a credible manner of transmitting energy from the power source to the working organs. In automotive systems, within the transmission unit, the gears change both torque and speed to fit the current vehicular usage and in industrial usage such as the lathes or milling machines, the gears constantly adapt power distribution to the cutting tools as required. By understanding tooth ratios, and gear systems in general, various machines can be matched for speed/torque requirements for transmission of power effectively. For example, wind generators invariably utilize gearbox units to achieve the right blade velocity and obtain the maximum possible energy yield while a manufacturing belt conveyor line employs gears in controlling both the velocity and the amount of torque necessary in moving the materials in a production line. This versatility in operations is important especially in today's complex engineering systems where gears are of immense value. To better understand the importance gears, play in industrial machinery, it's important to note that they not only act as a means for power transmission, but motion control and mechanical advantage as well. Within automotive manufacturing industries, gears are widely used in transmission systems, differentials, and power steering besides other such important parts that make automobiles to run as required[6].

In the same way, in the manufacturing industry, gears are critically essential in computerized numerical control machines and other equipment, used in determining speed and movement needed for quality production. Mining and construction industries, for example, also use gears in order to generate enough torque to power large machines in excavation, lifting and drilling etc. In addition, gears are noticeably used in energy industries, especially in wind turbines, gas turbines and hydroelectric systems , gearboxes are employed to increase energy output and efficiency[7] For example, in wind turbines gears control the flow of turbine blades to correspond with the speed of the generator and to produce the optimum output depending on prevailing wind conditions. In gas and steam turbines, those gears are used in transmitting mechanical energy to the electrical generators hence the continued dependence and contribution to the reliability and sustainability of energy systems. The significance of gears in these sectors is evidenced by the potential dangers of retaining them in substandard conditions in as much as slight defects can translate to huge losses and additional time out of operations. Appreciation of the utility and operations of gears is, therefore, critical in the quest to have long PDE and top performing gears its makes them the cornerstone our progress into the industrial realm[8].

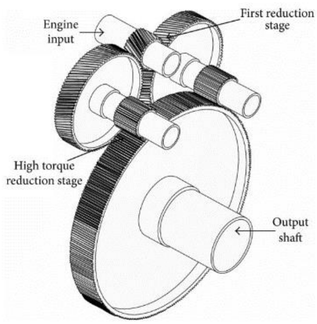

Fig.1 Key Functions of Gear Wheels

Objectives

- To analyze the behavior of gear wheels with various defects under static conditions, identifying subtle changes in performance caused by defects like cracks, tooth wear, and misalignment to improve early detection and predictive maintenance.

- To investigate the natural frequencies of gear wheels with and without defects, providing insights into how vibrational characteristics change due to specific defects and their implications for potential failures.

- To validate numerical findings from simulations using experimental results, ensuring the accuracy of finite element method (FEM) models by cross-checking with experimentally measured frequencies for practical industrial applications.

The paper has been structured to give a comprehensive analysis on gear wheel behavior with defects under static conditions. Section 2 reviews advancements in assessing the structural and dynamic performance with computational methods. Section 3 outlines the methodology used, including the development of 3D CAD models, FEM simulations, and modeling of various defects to analyze their impact on gear performance. Section 4 presents the results, focusing on the influence of defects on structural integrity, natural frequencies, and dynamic responses, and comparisons with baseline scenarios. Finally, Section 5 concludes with key findings, practical implications for predictive maintenance, and recommendations for future research to enhance gear reliability and longevity.

2. Literature review

Yu et al.[9]explains Recent advances have shown that the use of vibration analysis methods is very sensitive and reliable technologies for diagnosing faults in gear systems even under operating conditions. These methods are aimed at monitoring the local frequency spectrums caused by the gear systems in order to detect abnormalities that represent defects before they progress and cause much more severe damage. Out of all the applications, the Fourier Transform Analysis detects variation in the frequency of the time domain vibration signals in gear meshing frequency and their multiples. Wavelet Transform Analysis on the other hand provides time-frequency domain information and as such is ideal for capturing transients such as impacts arising from gear tooth breakage. Further, Envelope Detection singles out high frequency components in the vibration signal which proves to be beneficial in detecting local faults as features like cracks and pitting. As important as these techniques are, they entirely rely on vibration signals making them unsuitable for use in static or low vibration situations.

Panda et al. [10] summarised the state of focus on gear defect identification under dynamic conditions and highlighted the use of vibration analysis for real time condition monitoring of the rotating gears. But the discoveries of the paper also reveal a research gap that has not been conducted for gear behavior in static conditions, which are always encountered during maintenance or idle modes. The major objective of condition monitoring is to assist CBM by identifying degradation of the gears before reaching the catastrophic levels to incur additional costs of maintenance. The present research emphasizes the criticality of detection of faults at the preliminary stages to guarantee the availability of the system together with the safety of operation.

O. D. Mohammed and Rantatalo[11]reviewed and discussed methods of vibration based condition monitoring for detection of gear tooth faults with a focus on fault modeling and dynamic simulation. This concerned the function of vibration analysis in diagnosing shift in centrifugal responses associated with structural health or exciting forces. Some of them pointed out that systematic identification of poorly performing gears enables an efficient time/place arrangement for gear removal and/or replacement thereby eliminating a domino effect of average component failures and the associated costs. This paper outlines the available approaches and methods that have been proposed in the last decades for fault diagnosis and identifies their strengths and weaknesses.

Liu, Huang, and Xiang[12] developed a fault diagnosis model based on the finite element method (FEM) simulation and extreme learning machine (ELM) to tackle complexity encountered in fault classification of some mechanical systems which have particular characteristics of vibration. The method used includes building FEM models to generate fault signals and extracting time domain and time frequency domain features for training ELM, with actual vibration signal as testing data. It obtained fault classification accuracy ratios: from 85% to 92.5% for the different gear states and filled the gap between theoretical classification methods and their practicing application.

S. A. Mohammed, Ghazaly, and Abdo[13] experimentally studied vibro-diagnostic approaches that involve employing vibration characteristics of automobiles for determination of gearbox faults such as gear-tooth crack under several operating conditions. They used a test rig to study the response of the gearboxes due to vibrational signals for gears having cracks of different depths – 1mm, 2mm, and 3mm: the authors employed a feedforward neural network with the backpropagation method (NNBP) to classify the crack severity. The findings indicated that vibration amplitude rises with crack depth and that the highest fault detection accuracy obtained from the time-domain analysis was higher than that of the neural network method. The study also pointed to the problems arising from the technique when increase of the vibration level is insignificant and established statistical features in the time domain useful for fault detection.

Recent advances have shown that the use of vibration analysis methods is very sensitive and reliable technologies for diagnosing faults in gear systems even under operating conditions. These methods are aimed at monitoring the local frequency spectrums caused by the gear systems in order to detect abnormalities that represent defects before they progress and cause much more severe damage[14]. Out of all the applications, the Fourier Transform Analysis detects variation in the frequency of the time domain vibration signals in gear meshing frequency and their multiples. Wavelet Transform Analysis on the other hand provides time-frequency domain information and as such is ideal for capturing transients such as impacts arising from gear tooth breakage. Further, Envelope Detection singles out high frequency commponents in the vibration signal which proves to be beneficial in detecting local faults as features like cracks and pitting. As important as these techniques are, they entirely rely on vibration signals making them unsuitable for use in static or low vibration situations[15].

3. Problem Statement

In the same way, in the manufacturing industry, gears are critically essential in computerized numerical control machines and other equipment, used in determining speed and movement needed for quality production. Mining and construction industries, for example, also use gears in order to generate enough torque to power large machines in excavation, lifting and drilling etc. In addition, gears are noticeably used in energy industries, especially in wind turbines, gas turbines and hydroelectric systems; gearboxes are employed to increase energy output and efficiency. For example, in wind turbines gears control the flow of turbine blades to correspond with the speed of the generator and to produce the optimum output depending on prevailing wind conditions. In gas and steam turbines, those gears are used in transmitting mechanical energy to the electrical generators hence the continued dependence and contribution to the reliability and sustainability of energy systems. The significance of gears in these sectors is evidenced by the potential dangers of retaining them in substandard conditions in as much as slight defects can translate to huge losses and additional time out of operations. Appreciation of the utility and operations of gears is, therefore, critical in the quest to have long PDE and top performing gears its makes them the cornerstone our progress into the industrial realm.

4. Proposed Computational-Experimental Method combines CAD, FEM simulations, and experiments to analyse gear behaviour statically.

The method used in this study is called the Computational-Experimental Method, which enables to examine the operation of a dryer gear wheel used in paper mills comprehensively. This analysis incorporates 3D CAD geometry of the gear, Finite Element Method (FEM) analysis, and experimental validation for the assessment of gear structural health, natural frequencies, and defects prognosis under static loads. The key steps of the methodology are outlined

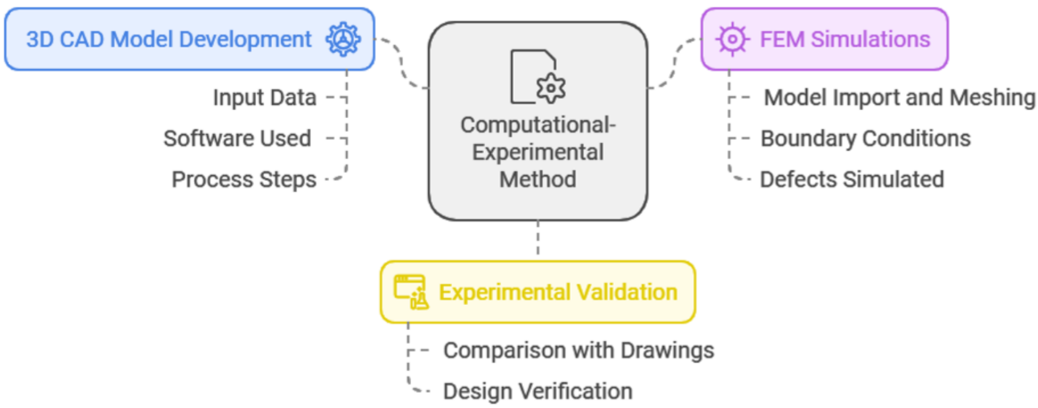

Fig.2 proposed method

4.1 3D CAD Model Development

The synthesis of a three-dimensional computer aided design model of the dryer gear wheel is an initial important task in the analysis followed by other simulations later on. It has several stages each of which, has to be done rightly to make sure the model corresponds to the actual system and can be subjected to analysis. When working with SolidWorks as the primary CAD tool creating a geometrically accurate 3D model from 2D technical drawings entails certain important steps. Here's a detailed breakdown of the working process:

1. Input Data: 2D Technical Drawings

The input data for the CAD model therefore has to be generated from 2D technical drawing. These drawings illustrate such important measurements and features essential for the accurate modeling. Critical parameters include

Number of Teeth (Z): This parameter defines the tooth count on the gear, which impacts the gear ratio and load distribution. The gear ratio i is given in eqn.(1)

$$i = \frac{z_2}{z_1} \quad (1)$$

where z_1 and z_2 represent the number of teeth on the driving and driven gears, respectively

Pitch Diameter (D): This is the diameter that it is referred as where the teeth of the gears come into contact with each other. The pitch diameter D is connected with the module mmm and number of teeth Z by the eqn.(2)

$$D = m.z \quad (2)$$

where m is the module, which determines the size of the teeth.

Module (m): This is one of the basic parameters, which describe the size of the gear teeth. This makes the module especially important since it will help prevent gears with meshing teeth from having different sizes. The module is typically calculated as the ratio of the pitch diameter to the number of teeth is given in eqn. (3)

$$m = \frac{D}{Z} \quad (3)$$

Pressure Angle (α): This is the point at which the gear teeth touch each other; standard gears are tilted between 14.5° – 20°. Pressure angle determines the load, and how closely and freely gears will engage with one another.

Material Specifications: Some of the gear material type includes the steel alloys and determine the strength, wear resistance and durability to the operational stresses, which are helpful for paper mill type of applications.

These dimensions, and specifications are important to apply and guarantee the suitable work of the gear in the mechanical system especially in critical operations.

2. Software Used: SolidWorks

The reason for choosing SolidWorks is because of it is a powerful parametric design tool capable of providing accurate models of complicated mechanical parts. SolidWorks makes it easy to model gears for 3D in that it follows a parametric design technique making it possible to change aspect such as gear size, the shape of the teeth and the pressure angle. If there are changes made to the model, then the features associated with it will adjust to that change to keep the overall consistency within the design process.

3. Process:

a. Base Profile Sketching

The first approach in the design procedure is drawing of 2D base profile sketch of the gear in SolidWorks.

Outer and Root Diameters: The outer diameter D_{out} defines the overall size of the gear, while the root diameter D_{root} refers to the diameter at the base of the teeth. These are critical for ensuring proper meshing with other gears in the system is given in eqn. (4)

D_{out} =D+2h and D_{root} =d-2h(4)

where h is the addendum (height of the tooth).

b. Extrusion

Once the base profile is drawn, the next step is extrusion to convert the 2D sketch into a 3D gear body. The extrusion process adds depth to the base profile, typically equal to the face width (b) of the gear is given in eqn.(5)

$b=\frac{D}{5}$(5)

This step creates the primary geometry of the gear, including the teeth, while the fillets and keyways are integrated during the extrusion process. These features are essential for ensuring that the gear can be attached securely to a shaft and function efficiently under load.

c. Circular Pattern for Teeth

The gear teeth profiles are made from the circular pattern in SolidWorks that clones the first tooth profile around the circumference of a gear. The teeth quantity for Z is defined by the necessary number of gear ratio and uniform, so that the meshing will be convenient.. The pattern tool places the teeth at equal intervals, with the following equation defining the angular spacing between each tooth is given in eqn. (6)

$\theta = \frac{360}{Z}$(6)

This tool ensures uniformity and precision in the design, which is critical for ensuring smooth gear engagement and even load distribution.

d. Additional Features

After the teeth are generated, additional features are added to the model:

Hub:The hub is the intermediate component of gear in contact with the shaft in order to transmit the torque. For protection against slippage, there is a provision for a keyway to retain the gear on to the shaft.

Mounting Holes: It is common to attach the gear in the system and thus the mounting holes are incorporated. These are intentionally positioned in order to be safely bolted and positioned at the final stage of integration's

e. Filleting

Fillets are used where there can be high stress concentration and normally at the roots of the gear teeth. Sharp edged and corner areas are the regions where stress concentration is observed and becomes a critical area due to crack initiation under load. As to the use of fillets, stress is evenly spread as a result of which the gear becomes more durable$K_t$is given in eqn.(7)

$$K_t = \frac{\sigma_{max}}{\sigma_{nominal}} (7)$$

where $\sigma_{max}$is the maximum stress at the edge and $\sigma_{nominal}$ is the average stress. The goal is to reduce $K_t$by rounding sharp corners, which increases the gear's life expectancy and performance under dynamic conditions.

4. Validation

The last step of the process is validation after the 3D model had been generated. The model is compared to the actual plan drawings done in 2D to ascertain if all the drawing is of optimum dimensions. Moreover, all engineering drawings are created from the 3D model, including all dimensions and tolerance required to build the product.

Comparison with 2D Drawings: The various dimensions from 3D model are further checked and compared with those from the 2D technical drawing to confirm the accuracy of the former.

Design Verification: The manufacturability of the model is also checked and keyways and mounting holes' positions are ensured for assembling and functional purposes.

In order to make an accurate conception of the geometry of the gear to be ready for FEM simulations, the 3D CAD model of the dryer gear wheel in SolidWorks will be developed as follows. This process involves sequence of operations starting from 2D base profile drawing, 3D extrusion, teeth replica by circular pattern tool, up to addition of such vital features as hub and key way. The last model is very likely to be most accurate and easy to manufacture among all of them. The resulting 3D model serves as foundation for other simulation analysis, which include stress analysis, natural frequency analysis, as well as identification of defects of the gear in as-real-as-possible condition[16].

4.2 Finite Element Method (FEM) Simulations: Detailed Process

The next stage of the research is to carry out FEM simulation using ANSYS to investigate and predict the behaviour of the gear under various scenarios especially with the defects. FEM is a robust numerical method of approximating structures as assemblage of smaller subdomains, such that system of mechanical equations representative of stress conditions in materials may be solved. This simulation makes it possible to estimate the behavior of the gear in practice and the influence of defects on the failure of the structure and gear resource. To present the simulated results in details, the steps for FEM simulation are briefly explained below[13].

1. Model Import and Meshing

Model Import: The first activity undertaken in the FEM simulation is passing of the 3D CAD model of the dryer gear wheel designed in SolidWorks into ANSYS. This is a very important simulation step when the initial design of the CAD model and all designed features (teeth, keyways, mounting holes, etc.) are moved to ANSYS.

SolidWorks to ANSYS Transfer: In any case, the model is saved in generic CAD format such as IGES, STEP etc which generally can be imported into ANSYS. That is a process where the data flow from the importing or transmitting model is compared with that of the original transmitting or exporting model to see if there are any disparities or incompatible differences.

Meshing: After the model has been imported the second step is meshing which means dividing of the model into elements. These elements form the basis of the Finite Element Analysis and are what will be employed to determine the performance of the gear under load.

- Element Type Selection: As for the types of elements, they have been chosen according to the geometry of the model and the type of analyses they are to perform. In gear systems, the most common use stiffening elements are employed in gear body and tooth.

- Mesh Refinement: A variety of mesh density is chosen to be finer in regions where it is assumed to be subjected to high stress levels such as near the gear teeth or in regions, which are likely to have defects. This leads to more actual stress and strain characters' estimates.

- Meshing Software Tools: ANSYS contains the enhanced tools to mesh the part in order to achieve the proper mesh topology that defines the geometry of the gear. DOI: The mesh quality significantly determines the precision of mesh-based simulation and the ability of reaching convergence throughout the analysis[17].

2. Boundary Conditions

Sometimes known as constraints placed on the gear, boundary conditions represent conditions under which the gear behaves or operates. Sounds: In case of the stated paper mill, boundary conditions mimic working conditions of the gear in terms of physical constraints and loads expected to be acted in normal use.

Constraints: They are bordering representations of the gear system for instance the location where the gear is fixed or where it engages the shaft. These are usually called displacement constraints, which are constraints where the desired displacement components (for instance, rotation or translation) are limited. For example, the gear may be limited at the hub to oppose certain motion or permit only its rotation in one or several planes.

Applied Loads: The loads applied here are those forces which are brought by the gear during its functioning. These include:

- Torque: A twist is then applied on the gear to emulate the forces in terms of rotations that the gear exerts from the motor.

- Pressure: In the case of gears, direct contact is made with engaging teeth and contact pressure acting between the teeth is applied as in the case of loads transferred during the meshing.

- Thermal Loads: They also require thermal expansion or heat induced stresses maybe modelled sometimes as in the case with paper mill settings.

These boundary conditions ensure that the gear's behavior is accurately modeled under real-world operating conditions.

3. Defects Simulated

The FEM simulation is especially valuable in understanding the gear behaviour when certain defects are present. There are different kinds of damages for a similar car as in the real world; for instance, one may have some cracks or some parts may be worn out. The following defects are simulated:

Broken Teeth: the complexity of a gear system, the non-functioning of one or more teeth is emulated to understand the impacts that occur to the load and subsequently the performance of the gear. When a tooth is missing, the load transferred to the neighbouring teeth and increases stress of certain parts of them and causes failure.

- Modelling Process: The missing teeth are just taken out of the from the mesh and the analysis is then performed to determine how the load is reallocated to the rest of the teeth.

- Impact on Load Distribution: The simulation assists in identifying the impact of lack of teeth on the gear relationship of supplying torque and uncover localized pressure concentrations that lead to additional damage.

Root Wear: At this specific wear location, it mimics what happens when wear is progressive on the gear and tooth root. Wear generally results in a decrease in effective thickness of the gear, and increases stress concentration at tooth root.

- Modelling Process: Usually wear is studied in the frequency domain; with a less thickness of the tooth root or incorporation of material damage in the root region.

- Impact on Structural Integrity: This wear results in stress concentrations that are critical in determination of possibilities of cracks development or failure in gears that are used continuously.

Misalignment: Mismatching of the mating gears is very widespread, thus leading to instability and uneven pressure distribution, causing vibrations, and in the end, wear of the gears.

- Modelling Process: To model misalignment, the alignment of the gear under consideration is skewed a little from alignment with its companion gear.

- Impact on Load Distribution: This causes uneven meshing, leading to localized regions of higher stress and potentially inducing dynamic forces that lead to vibration and noise. The simulation can predict how misalignment will impact gear performance and lifespan[18].

4. Types of Analysis

After meshing and defect are applied to the model, a number of tests are run to observe behaviour of gear under different conditions.

a. Stress Analysis

Stress analysis is the most common analysis that is conducted in order to help determine where stress is at its peak. It assists in extrapolating where cross talking might happen when operating under, for instance, a load condition.

Stress Concentration Areas: Various regions of a gear system for instance in the tooth root the stresses are high. FEM simulations point out these areas and makes the engineers judge whether the gear will fail because of material overload.

Failure Prediction: Based on the obtained stress distribution, the possible failure location may be predicted applying failure criteria like von Mises yield criterion or maximum normal stress theory[18].

b. Natural Frequency Analysis

The essence of natural frequency analysis is to determine by the way these defect frequencies influence the gear's natural frequencies. They are the frequencies at which the Gear will vibrate when interfered and are of great significance in deciding vulnerability to resonance.

- Effect of Defects: Structural imperfections such as crack, tooth breaking, wear or misalignment alter the gear stiffness and consequently alter its natural frequencies.

- Resonance Risk: Gear which operates in the frequency at which it resonates is prone to high vibrations whereby can cause either high wear or failure of the gear. These analysis decisions assist in evaluating the possibility of resonance under various loading conditions and with various forms of defects.

c. Modal Analysis

Modal analysis is employed in analyzing the vibrational behavior of the gear. It enables determination of how the gear system respond in dynamic force condition especially when configured with defects.

- Vibrational Modes: Various modes of vibrations such as bending, torsional, etc., are distinguished and the frequency of vibrations for each mode is indicated.

- Impact of Defects: Distortions, for example, cracks or misalignments may result in changes of the vibrational frequencies thus changes in dynamic responses. Thus, all the obtained results contribute to understanding the role of defects in the total vibrational response of the gear that can be used for early failure detection.

d. Fatigue Life Prediction

Fatigue live prediction can be employed to determine the duration of the continued usage of the gear, consequent to the applied loads, defects and the properties of the materials.

- Fatigue Damage: Gears undergo cyclic loading, which causes material fatigue over time. FEM simulations can predict the number of cycles a gear can withstand before failure occurs. Gears are subjected to dynamic loading that results to material fatigue and failure. Computational models of FEM can help to determine the number of cycles, after which the gear can fail.

- Defect Impact on Fatigue: There are micro cracks and or wear on gear surfaces and so it increases the rate of fatigue and the gear will not last long. The simulation also incorporates how these defects can undermine the loading capacity of the gear in a repeated manner.

ANSYS FEM simulations in this paper reveal valuable information about the response of the dryer gear wheel under various operating conditions and defect profiles. The deficiencies include the broken teeth, root's wear, and misalignments that the engineering simulation can predict how these deficiencies will affect stress distribution, natural frequencies, and performance of the gear. The specific form of analysis referred to as stress, natural frequency, modal, and fatigue life enable determination of structural weakness or possible failure and act as a tool for determining the maintenance schedule and improving the design for greater reliability and performance[19].

Model prepared in solid works for fem analysis, design related data is not attached as it is proprietary data of Rajahmundry paper mill.

Fig.3 Rajahmundry Paper Mill Pulley Model

5. Result and Discussions

Results of the test indicate that gear wear, root defects, and broken teeth significantly influence the structural and dynamic behavior of gear systems under static conditions. The wear was found to reduce deformation but increase stress concentration with risks of fatigue. This will show that defects can bring lower natural frequency and thus gears prone to be set under resonance at lower operating speed in comparison with intact systems; harmonic analysis, though reveals amplitude for decrease in displacement and velocities yet a rapid increase in acceleration corresponding to vibrational mode indicates a high susceptibility at excitations toward frequencies. These results indicate the need for predictive maintenance to reduce risks, enhance performance, and prolong gear life.

Simulation and Experimental Results

Structural Analysis

Table .1 Structural Analysis of Gear Wear: Deformation, Elastic Strain, and von-Mises Stress Trends

Gear ware	Total Deformation (mm)			Equivalent Elastic Strain (mm/mm)			Equivalent (von-Mises) Stress (Mpa)		
	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average
0% ware	0	1.3673	0.57011	3.85E-06	3.14E-03	5.12E-04	0.29277	626.93	96.923
10% ware	0	1.3341	0.53303	2.12E-06	3.18E-03	5.34E-04	0.36319	633.14	100.74
15% ware	0	1.3238	0.5285	2.80E-06	3.05E-03	5.34E-04	0.48204	608.6	100.75
20% ware	0	1.309	0.52367	3.87E-06	3.06E-03	5.33E-04	0.51058	611.27	100.62
30% ware	0	1.2779	0.50848	3.86E-06	2.94E-03	5.35E-04	0.48431	586.1	101.05
50% ware	0	1.2035	0.48668	3.73E-06	2.77E-03	5.29E-04	0.43573	553.48	99.812

The structural analysis primarily focuses on the deformation, equivalent elastic strain, and von-Mises stress for varying percentages of wear (0%, 10%, 15%, 20%, 30%, and 50%). The following trends were observed:

Total Deformation:

The gear's deformation decreases slightly with wear, with the maximum deformation decreasing from 1.3673 mm at 0% wear to 1.2035 mm at 50% wear, due to stress and strain redistribution.Effect of Wear on Gear Deformation is shown in Fig.4

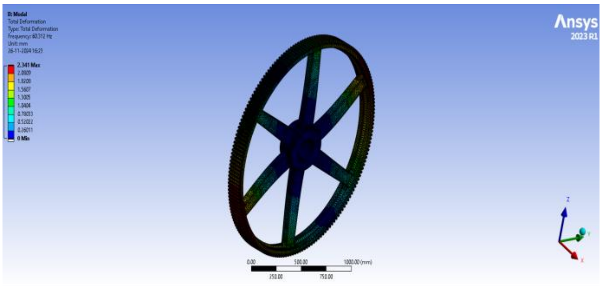

Fig.4 Effect of Wear on Gear Deformation

Equivalent Elastic Strain:

The elastic strain is virtually independent of the wear level with only slight differences. For example, the strain at maximum is 2.77E-03 mm/mm at 50% wear and 3.14E-03 mm/mm at 0% wear. This means that although surface condition and local behavior change due to wear, strain capacity of the material does not change much along different wear levels.

Equivalent (von-Mises) Stress:

Variations have occurred for von-Mises stress with wear but were not of a significant increase. As an example, maximum von-Mises stress is changed from 626.93 MPa at 0% wear to 633.14 MPa at 10% wear; after that it reduces to 553.48 MPa at 50% wear.

Modal Analysis

Table.2 Modal Analysis of Gear Wear: Natural Frequencies Across Wear Percentage

Mode	Frequency [Hz]					
	0% ware	10% ware	15% ware	20% ware	30% ware	50% ware
1	60.312	60.677	60.892	61.132	61.687	63.063
2	60.312	60.68	60.893	61.133	61.69	63.066
3	64.801	65.282	65.529	65.807	66.455	68.033
4	86.436	87.079	87.442	87.847	88.782	91.116
5	99.133	99.858	100.21	100.6	101.5	103.65
6	99.135	99.861	100.21	100.6	101.51	103.65
7	214.63	216.77	217.42	218.22	220.15	224.84
8	214.64	216.78	217.47	218.25	220.16	224.86
9	219.34	221.33	222.15	223.07	225.22	230.2
10	229.3	231.89	233.02	234.29	237.2	243.03
11	232.34	234.38	235.11	235.95	237.99	244

12	236.11	238.28	238.98	239.86	241.91	247
13	236.12	238.29	239.04	239.86	241.93	247.03
14	407.56	411.99	413.83	415.91	420.64	431.43
15	407.58	412.02	413.86	415.91	420.66	431.46
16	511.92	513.7	514.42	515.22	517.07	521.16
17	511.94	513.72	514.44	515.24	517.09	521.19
18	515.19	516.94	517.7	518.55	520.52	524.95

In the first mode, for example, the frequency at 0% wear is 60.312 Hz whereas that at 50% wear is 63.063 Hz and similar trends are found at higher modes. Material loss causes stiffening that reduces the mass of the gear and hence results in higher frequencies. The frequency shift is more pronounced at higher modes, such as in the 14th mode, where the frequency increases from 407.56 Hz at 0% wear to 431.43 Hz at 50% wear, indicating that wear enhances the gear's stiffness and shifts its resonance to higher frequencies.

HarmonicAnalysis

Table.3 Harmonic Analysis of Model Frequencies Across Wear Levels

Mode	Frequency [Hz]					
	0% ware	10% ware	15% ware	20% ware	30% ware	50% ware
1	52.5	107	109	109	109	109
2	105	154	158	158	158	158
3	157.5	201	207	207	207	207
4	210	248	256	256	256	256
5	262.5	295	305	305	305	305
6	315	342	354	354	354	354
7	367.5	389	403	403	403	403
8	420	436	452	452	452	452
9	472.5	483	501	501	501	501
10	525	530	550	550	550	550

Table.4 Harmonic Analysis of Displacement Amplitudes Across Wear Levels

Mode	displacement amplitude(mm)					
	0% ware	10% ware	15% ware	20% ware	30% ware	50% ware
1	0.12412	4.09E-03	3.69E-03	3.79E-03	3.87E-03	4.45E-03
2	5.05E-03	2.60E-04	2.00E-04	2.19E-04	2.10E-04	3.22E-04
3	3.85E-04	1.17E-04	1.25E-04	1.17E-04	1.28E-04	7.96E-05
4	2.72E-05	1.51E-04	1.47E-04	1.42E-04	1.51E-04	1.22E-04
5	7.49E-05	1.32E-04	1.26E-04	1.22E-04	1.29E-04	1.09E-04
6	6.59E-05	1.08E-04	1.00E-04	9.74E-05	1.04E-04	8.63E-05

7	4.59E-05	8.45E-05	7.68E-05	7.40E-05	8.00E-05	6.32E-05
8	1.92E-05	6.19E-05	5.15E-05	4.82E-05	5.55E-05	3.57E-05
9	3.99E-05	2.52E-05	2.71E-05	3.25E-05	8.28E-06	4.36E-05
10	4.25E-04	1.63E-04	9.82E-05	1.04E-04	1.01E-04	1.46E-04

Table.5 Harmonic Analysis: Velocity Amplitudes Across Wear Levels

Mode	velocity amplitude(mm/s)					
	0% ware	10% ware	15% ware	20% ware	30% ware	50% ware
1	13505	1846.7	1733.1	1777.8	1816.6	2086.9
2	2199.8	243.24	196.87	215.85	207.18	317.3
3	376.78	186.71	211.99	197.86	216.04	134.65
4	47.271	366.62	381.21	368.37	391.1	316.8
5	203.71	454.78	461.94	448.91	475.34	399.08
6	258.1	496.73	496.39	481.93	512.91	427.01
7	244.62	504.66	492.11	474.32	513.05	405.51
8	133.78	464.64	415.19	389.08	447.84	288.1
9	351.6	232.14	268.54	322.39	82.047	432.08
10	4621.4	1807.3	1173.1	1236.3	1206.7	1740

The focus is on how a gear responds under cyclic loadings of various frequencies, hence its harmonic analysis. These are analyzed based on displacement, velocity, and mode frequencies that result at different wear levels for understanding dynamic behavior of gears.

Displacement Amplitude:

With an increase in wear, the displacement amplitude shows a clear decrease. For example, the maximum displacement is 0.12412 mm at 0% wear and decreases to 4.45E-03 mm at 50% wear. This trend indicates that the gear becomes stiffer with increasing wear, which in turn reduces the amplitudes of displacement under harmonic excitation. The gear is less flexible and cannot deform easily under dynamic loads due to the decreased material at higher percentages of wear.Displacement Amplitude vs. Wear Percentage is given in Fig.5

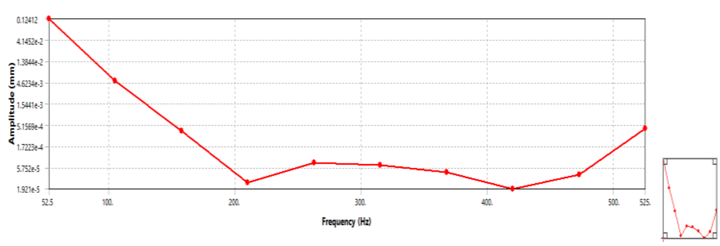

Fig.5 Displacement Amplitude vs. Wear Percentage

Velocity Amplitude:

The velocity amplitude also decreases with increased wear. At 0% wear, the maximum velocity amplitude is 13505 mm/s, which drops to 2086.9 mm/s at 50% wear. This further reinforces the notion that as wear progresses, the gear's ability to undergo deformation and movement under dynamic conditions diminishes, leading to lower velocities in response to the same harmonic forces.

Root Wear

Structural analysis

Table.6 Total Deformation, Equivalent Elastic Strain, and Von-Mises Stress for Different Root Wear Levels

Root wear	Total Deformation (mm)			Equivalent Elastic Strain (mm/mm)			Equivalent (von-Mises) Stress (Mpa)		
	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average
15% ware	0	1.1691	0.49693	3.62E-05	2.41E-03	5.63E-04	2.048	472.6	96.284
30% ware	0	1.2097	0.51893	1.50E-05	2.46E-03	5.54E-04	2.0968	482.33	95.492
45% ware	0	1.2372	0.52672	3.06E-05	2.54E-03	5.62E-04	1.6106	503.12	96.754
60% ware	0	1.2582	0.5346	4.02E-05	2.56E-03	5.69E-04	2.8712	507.34	98.578

Conduct structural analysis for total deformation, equivalent elastic strain, and von-Mises stress with various amounts of root wear (15%, 30%, 45%, and 60%). We have obtained several important trends in the findings:

As wear percentage increases, the gear exhibits higher total deformation, equivalent elastic strain, and von-Mises stress. The total deformation increases from 1.1691 mm at 15% wear to 1.2582 mm at 60% wear; hence, the structural integrity and stiffness are decreased because of the loss of material at the root. Equivalent elastic strain increases from 2.41E-03 mm/mm at 15% wear to 2.56E-03 mm/mm at 60% wear, meaning more localized deformation occurs near the root.The von-Mises stress increases from 472.6 MPa at 15% wear to 507.34 MPa at 60% wear, pointing out stress concentration at the worn root that raises the probability of fatigue and failure. However, even with these increases, the average von-Mises stress is seen to be relatively constant, implying stable load distribution across the gear teeth.

Modal analysis

Table.7 Modal Analysis Results - Natural Frequencies at Different Levels of Wear

Mode	Frequency [Hz]			
	0% ware	10% ware	15% ware	20% ware
1	64.127	63.141	62.641	62.348
2	64.151	63.146	62.658	62.37
3	69.213	68.112	67.571	67.248

4	92.138	90.466	89.623	89.139
5	105.94	104.67	104	103.56
6	106.02	104.72	104.06	103.64
7	233.3	230.44	229.09	227.7
8	233.54	230.64	229.38	227.99
9	234.29	231.52	230.08	228.98
10	250.91	247.5	245.69	244.53
11	251.44	248.02	246.45	245.01
12	255.85	252.52	251.05	249.56
13	256.18	252.79	251.24	249.75
14	440.83	435.51	432.56	430.57
15	440.98	435.58	432.68	430.69
16	529.92	528.15	526.89	526.27
17	530.25	528.38	527.26	526.57
18	533.35	531.25	529.86	529.05

Modal analysis shows that as wear increases, the natural frequencies of the gear system decrease slightly. For instance, in the first mode, the frequency drops from 64.127 Hz at 0% wear to 62.348 Hz at 20% wear, and this trend is observed across most modes. The reduction in frequency is mainly due to the loss of stiffness as material is removed from the gear root, making the gear more flexible. This decrease in natural frequency suggests the gear system becomes more prone to resonant frequencies at lower speeds, potentially causing vibrations and mechanical failure. The frequency reduction is more noticeable in higher modes, indicating that higher-order vibrational modes are more affected by root wear.

Harmonic Analysis

Table.8 Harmonic Analysis of Mode Frequencies at Different Levels of Root Wear

Mode	Frequency [Hz]			
	15% ware	30% ware	45% ware	60% ware
1	55	100	100	100
2	110	150	150	150
3	165	200	200	200
4	220	250	250	250
5	275	300	300	300
6	330	350	350	350
7	385	400	400	400

8	440	450	450	450
9	495	500	500	500
10	550	550	550	550

Table.9 Harmonic Analysis of Displacement Amplitude for Different Root Wear Levels

Mode	displacement amplitude(mm)			
	15% ware	30% ware	45% ware	60% ware
1	0.10882	9.43E-03	9.14E-03	9.02E-03
2	5.77E-03	1.04E-03	1.02E-03	1.02E-03
3	6.78E-04	2.33E-04	2.27E-04	2.30E-04
4	1.58E-04	7.98E-05	7.72E-05	7.96E-05
5	6.55E-05	5.03E-05	4.86E-05	5.02E-05
6	5.67E-05	5.69E-05	5.54E-05	5.63E-05
7	7.78E-05	8.43E-05	8.29E-05	8.32E-05
8	1.32E-04	1.49E-04	1.48E-04	1.48E-04
9	3.47E-04	4.13E-04	4.23E-04	4.28E-04
10	8.33E-04	7.15E-04	6.53E-04	6.17E-04

Table.10 Harmonic Analysis of Velocity Amplitude for Different Root Wear Levels

Mode	velocity amplitude(mm/s)			
	15% ware	30% ware	45% ware	60% ware
1	12996	3721.6	3609.2	3561
2	2757.7	924.25	902.64	901.93
3	728.78	368.34	358.73	363.66
4	301.83	196.9	190.43	196.51
5	195.53	178.59	172.73	178.41
6	243.75	274.99	268.09	272.32
7	455.09	532.51	523.52	525.26
8	1006.8	1188.5	1181.5	1179.3
9	3355.3	4079.4	4177.1	4222.3
10	9949.8	8539.5	7792.4	7368.3

Harmonic analysis means how gear behaves under different cyclic loads and varies in frequency. The gear's displacements, accelerations, with mode frequencies will describe the dynamic responses of this gear system as root wear progresses.

As wear increases, the amplitude of displacement decreases. For example, in the first mode, displacement reduces from 0.10882 mm at 15% wear to 9.02E-03 mm at 60% wear, which signifies that the gear becomes stiffer and avoids deformation under dynamic loading. It is because of material redistribution around the root wear zones. The velocity amplitude of a complex pattern; for the first mode, it degrades from 12,996 mm/s at 15% wear up to 3,561 mm/s at 60% wear. In the higher modes, it increases-for example, in the ninth mode, the velocity rise was from 3,355.3 mm/s to 4,222.3 mm/s; that is, lower modes have damped by increased stiffness while the higher modes are much more sensitive to wear. However, the modes do not change much with various amounts of wear; for instance, even at 30%, 45%, and 60% wear level, the first mode is still at 100 Hz. Hence, frequency does not depend on wear, but its magnitudes certainly do change, which can be attributed to the nature of wear itself

Broken Gear teeth

Structural Analysis

Table.11 Structural Analysis Results for Broken Gear Teeth

broken teeth	Total Deformation (mm)			Equivalent Elastic Strain (mm/mm)			Equivalent (von-Mises) Stress (Mpa)		
	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average
35 teeth	0	1.6482	0.71701	1.53E-06	3.15E-03	4.62E-04	0.30697	629.45	81.692
45 teeth	0	1.9013	0.84967	1.52E-06	3.34E-03	4.62E-04	0.30398	667.25	81.767
60 teeth	0	1.17E-03	9.90E-04	8.87E-10	3.37E-07	4.84E-08	3.37E-05	6.73E-02	8.21E-03

The total deformation, elastic strain, and von-Mises stress are calculated in the structural analysis to emphasize the mechanical behaviour of the gear system under static load conditions.

As the number of cracked teeth increases, total deformation goes up, from 1.6482 mm for 35 cracked teeth up to 1.9013 mm for 45 teeth, which shows that the structure of gear softens under load; in case the number of the crack exceeds 60 then, deformation dramatically falls to the value of 0.00117 mm, which shows gear failure. Elastic strain presents little fluctuation between 35 and 45 broken teeth but drops dramatically to 3.37E-07 mm/mm for 60 broken teeth, indicating bad load distribution due to missing material. The von-Mises stress is higher with more broken teeth: from 629.45 MPa for 35 teeth, to 667.25 MPa for 45 teeth but remains very stable on average over all the scenarios. For 60 broken teeth, the stress significantly decreases and indicates that the gear cannot bear the load anymore and probably is about to fail.

Modal Analysis

Table.12 Modal Analysis Results for Broken Gear Teeth

Mode	Frequency [Hz]		
	35 teeth	45 teeth	60 teeth
1	61.301	61.335	55.364
2	62.121	62.453	56.967
3	66.351	66.798	64.938
4	88.053	88.465	88.116
5	100.55	100.76	90.847
6	102.83	103.47	93.448

7	219.05	220.22	214.4
8	220.84	221.66	215.53
9	222.72	222.74	217.37
10	236.95	237.71	229.33
11	237.48	239.38	230.68
12	240.82	241.02	234.4
13	244.75	250.59	242.34
14	414.35	417.14	411.57
15	419.94	422.61	413.39
16	521.48	521.3	517.05
17	523.46	524.03	520.25
18	527.77	532.43	531.11

Modal analysis evaluates the natural frequencies of the system, which expose how the gear will resonate to vibrational forces and establish the frequencies at which possible resonance may take place.

The more the broken teeth, the lower the natural frequency of the gear. First mode frequency remains the same at 61.301 Hz and 61.335 Hz for 35 and 45 broken teeth, respectively. However, for 60 broken teeth, it significantly goes down to 55.364 Hz, as there is a decrease in stiffness. Similar patterns are noticed in higher modes also, wherein the frequencies for 60 broken teeth are less than others. This reduces the frequency of this gear, making it more vulnerable to resonance at lower operating speeds that may lead to excessive vibration and an increased risk of failure.

Harmonic Analysis

Table.13 Harmonic Analysis of Frequencies for Broken Gear Teeth

Mode	Frequency [Hz]		
	35 teeth	45 teeth	60 teeth
1	100	100	100
2	150	150	150
3	200	200	200
4	250	250	250
5	300	300	300
6	350	350	350
7	400	400	400
8	450	450	450
9	500	500	500
10	550	550	550

Table.14 Harmonic Analysis of Displacement Amplitude for Broken Gear Teeth

Mode	displacement amplitude(mm)		
	35 teeth	45 teeth	60 teeth
1	1.08E-02	1.10E-02	9.49E-03
2	1.65E-03	1.63E-03	1.53E-03
3	5.77E-04	5.72E-04	5.54E-04
4	2.91E-04	2.69E-04	2.61E-04
5	2.09E-04	2.02E-04	1.96E-04
6	1.84E-04	1.80E-04	1.78E-04
7	2.00E-04	2.01E-04	2.14E-04
8	2.60E-04	2.45E-04	2.52E-04
9	6.63E-04	6.34E-04	7.21E-04
10	6.61E-04	7.04E-04	6.19E-04

Table.15 Harmonic Analysis - Velocity Amplitude for Broken Gear Teeth

Mode	velocity amplitude(mm/s)		
	35 teeth	45 teeth	60 teeth
1	4262	4357.6	3748.4
2	1461.7	1452.2	1362.3
3	911.25	903.48	874.74
4	717.68	663.06	645
5	742.01	718.43	697.21
6	888.46	868.89	861.35
7	1266.3	1271.1	1351.7
8	2074.8	1954.9	2015.1
9	6542	6260.3	7118.2
10	7899.1	8408.1	7388.5

Mode	velocity amplitude(mm/s)		
	35 teeth	45 teeth	60 teeth
1	4262	4357.6	3748.4
2	1461.7	1452.2	1362.3
3	911.25	903.48	874.74
4	717.68	663.06	645
5	742.01	718.43	697.21
6	888.46	868.89	861.35
7	1266.3	1271.1	1351.7
8	2074.8	1954.9	2015.1

9	6542	6260.3	7118.2
10	7899.1	8408.1	7388.5

Harmonic analysis examines the response of the gear system to cyclic loads at various frequencies and focuses on the amplitudes of displacement, velocity, and acceleration.

Both the displacement and velocity amplitudes decrease with the increase in the number of broken teeth. For example, in the first mode, the displacement amplitude has reduced from 1.08E-02 mm for 35 teeth to 9.49E-03 mm for 60 teeth, and velocity amplitude dropped from 4262 mm/s for 35 teeth to 3748.4 mm/s for 60 teeth. This indicates that the gear system stiffens and loses the capacity to deform, thus respond to dynamic forces, as the number of fractured teeth increases. Such reduced flexibility and response may imply structural degradation in which the gear is susceptible to brittle failure or incorrect engagement with other teeth.

Harmonic Analysis of Healthy Gear Wheel At 100 Rpm

Table.16 Harmonic Analysis of Healthy Gear Wheel at 100 RPM

for healthy gear wheel		
Frequency [Hz]	displacement amplitude(mm)	velocity amplitude(mm/s)
52.5	9.76E-03	3.2187
105	1.80E-03	1.1859
157.5	6.09E-04	0.6031
210	3.20E-04	0.42202
262.5	2.01E-04	0.33203
315	1.41E-04	0.27977
367.5	1.08E-04	0.24942
420	9.06E-05	0.23912
472.5	9.30E-05	0.27612
525	2.77E-04	0.9123

The displacement and velocity amplitudes of the gear wheel decrease as frequency increases, following typical mechanical system behaviour. At lower frequencies, displacement amplitude starts at 9.76×10^{-3} mm at 52.5 Hz and decreases to a minimum of 9.06×10^{-5} mm at 420 Hz. A slight increase is observed at 472.5 Hz, followed by a significant peak at 525 Hz, where displacement reaches 2.77×10^{-4} mm. Similarly, velocity amplitude peaks at 3.2187 mm/s at 52.5 Hz and drops to 0.23912 mm/s at 420 Hz, with a small rise at 472.5 Hz and a larger increase at 525 Hz to 0.9123 mm/s. These trends suggest stable gear behavior under harmonic excitation, but the increase in amplitude at certain frequencies points to potential resonance effects, which warrant further investigation to ensure the gear's safety and longevity under dynamic conditions.

Overall Impact of Gear Wear

The combined results from the structural, modal, and harmonic analyses indicate that the gear becomes stiffer as wear increases; that is, deformation and strain decrease. However, this increase in stiffness leads to higher stress concentrations that may cause localized failures. The increase in natural frequency with wear indicates that the gear becomes more prone to excitations at higher frequencies than without wear, which changes the nature of its resonance character and makes it more sensitive to fatigue or failure within that frequency range. Furthermore, displacement and velocity amplitudes' decrease shows that the dynamic character of the gear becomes harder and that the gear dynamics would be more dangerous if taken under uncontrolled fluctuation load.Impact of Wear on Gear Structural and Dynamic Properties is decipted in Fig.6

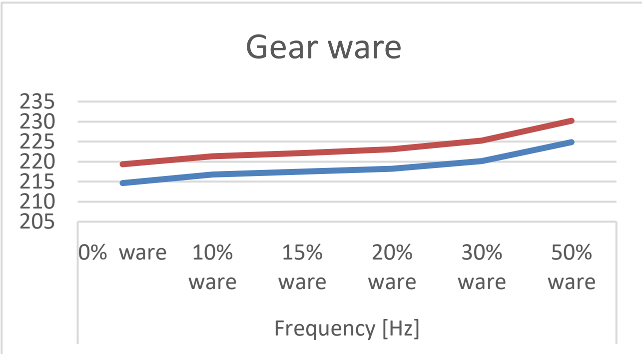

Fig.6Impact of Wear on Gear Structural and Dynamic Properties

Effect of Root Wear on Gear Wheel Modal and Harmonic Behaviour

Root wear in gear wheels significantly affects both their modal and harmonic behavior, thereby changing their dynamic performance with time.

Effect on Modal Behaviour

As the root wear advances, the natural frequencies of the gear wheel are decreased owing to the material loss at the root, which reduces stiffness and increases flexibility of the gear. For instance, the frequency of the first mode changes from 64.127 Hz at 0% wear to 62.348 Hz at 20% wear. This reduction is more significant at higher-order vibrational modes, making the gear susceptible to resonant frequencies at low operating speeds. If not resolved, this could cause excessive vibration and possibly mechanical problems.The Effect of Root Wear on The Frequency Of A Gear Wheel is shown in Fig.7

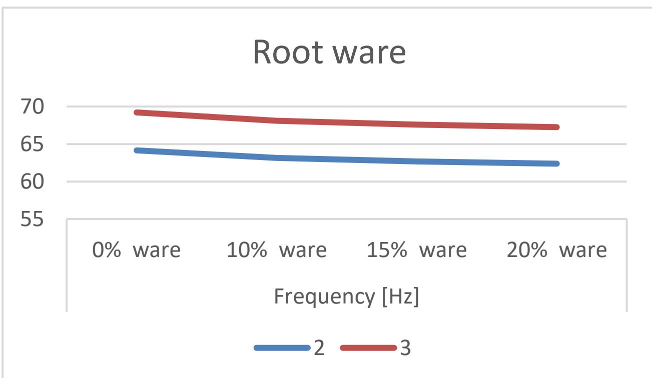

Fig.7 The Effect of Root Wear on The Frequency of A Gear Wheel.

Effect on Harmonic Behaviour:

Root wear has been analyzed through harmonic analysis to affect gear displacement and acceleration amplitudes during cyclic loading. Displacement amplitudes decrease with an increase in wear, and the stiffness has increased locally in those areas of material redistribution, which controls deformation under harmonic forces. Acceleration amplitudes follow a very complex pattern where the lower modes lose acceleration, while the higher modes gain acceleration. For instance, at 15% wear, the acceleration in the ninth mode was 3355.3 mm/s² and reached 4222.3 mm/s² at 60% wear, thus indicating that higher frequencies are sensitive to wear. Overall, the root wear reduces the natural frequencies while changing the gear's response to harmonic forces, and therefore, the monitoring and maintenance will prevent potential failure.

Impact of Broken Teeth

The analysis of broken teeth reveals significant impacts on both the structural and dynamic behaviour of the gear systemRelationship Between The Number Of Broken Teeth In A Gear And Certain Dynamic Characteristics is shown in fig.7

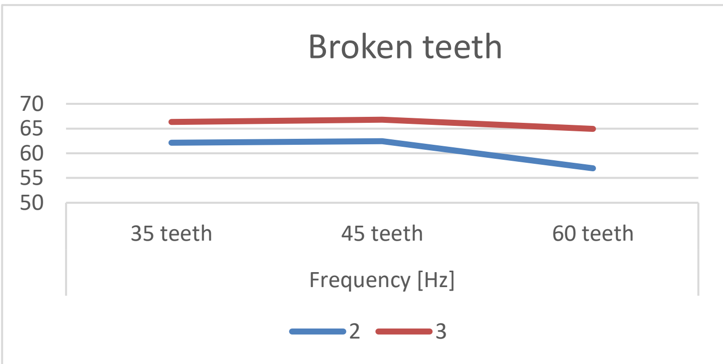

Fig.7The Relationship Between The Number Of Broken Teeth In A Gear And Certain Dynamic Characteristics.

With the increase in broken teeth, both structural and dynamic behavior of the gear degrades. Overall deformation and strain increase with a sharp peak at moderate damage levels such as 35 and 45 broken teeth but drastically drops with more than 60 broken teeth, indicating probable failure. Von-Mises stress also increases, meaning the stress concentrations on the remaining teeth are higher. The more broken teeth it has, the less stiff and more prone to resonance at a lower frequency, and the natural frequencies of the gear go down. This increases the risk of failure. A harmonic analysis will show displacement and velocity amplitudes decrease; acceleration amplitudes increase significantly, which may indicate very high intensities in certain frequency ranges leading to further damage or even failure.

Discussion

The results from these studies are very important inputs to the understanding of defective gear wheel behavior under static conditions. A key message here is that such analyses, structural and dynamic alike, are critical in the discussion of performance degradation.It has been demonstrated that both broken-teeth and root-erosion wear significantly impact deformation as well as stress distribution. With increasing wear, the redistribution of stress to unaffected regions increases local concentrations, thereby accelerating fatigue and raising the likelihood of failure. The effects are more pronounced with broken teeth, as they decrease stiffness and reduce natural frequencies, making the gear more prone to resonance under operational conditions. Modal analysis further revealed that defects lead to noticeable shifts in vibrational frequencies of the system. Broken teeth and root wear induce reduced stiffness and increase flexibility, and hence make the system more vulnerable to resonance-induced vibrations. Harmonic analysis completed these results by showing that wear and defects change the dynamic response of the gear. Low displacement amplitudes signify stiffness increase but higher acceleration amplitudes at specific frequencies point out increased sensitivity to high-frequency vibrations. These changes are important since they have a tendency to amplify dynamic forces and, in due course of time, may further damage the structure. Interaction between structural integrity and dynamic performance points towards the continuous monitoring of gears, even in high-stress applications. Predictive maintenance strategy, based on finite element method simulations and harmonic analysis, is quite important for identifying defects in advance and avoiding failures. This study provides a detailed framework for assessing gear defects under static conditions, thus filling in the gaps of previously conducted studies that were oriented toward dynamic conditions, and provides action-oriented information to improve design and maintenance of gear systems.

6. Conclusion and Future works

The conclusions that are drawn from this experiment indicate critical insights in understanding how gear wear, comprising broken teeth and root wear, affects the structural integrity and dynamic performance of the gear systems. Structural analysis established that wear increases the levels of stress concentrations and simultaneously decreases deformation due to material loss in localized areas. For instance, when more than 60 teeth are broken, a significant reduction in bearing capacity occurs, leading to possible catastrophic failure. Modal analysis indicated that wear decreases the natural frequencies of the gear system, thus making it more flexible and prone to resonance at lower frequencies, which may cause severe vibrations and further damage. Harmonic analysis revealed a paradoxical trend: while displacement and velocity amplitudes decrease due to increased stiffness, acceleration amplitudes in higher vibrational modes rise, exposing the system to risks associated with high-frequency excitations.

The future scope for research on gear systems consists of dynamic condition analysis incorporating realistic operating loads like torque fluctuation, transient response, and environmental parameters, so that the phenomenon of resonance and transient vibrations could be found. Advanced real-time monitoring techniques such as vibration analysis, acoustic emission sensors, and thermal imaging need to be devised so that predictive maintenance ability improves with continuous health monitoring of the system, accompanied by timely interventions. Leverage machine learning algorithms to analyze massive amounts of data from these systems for real-time defect detection, classification of the extent of wear, and accuracy of maintenance. Experimental validation of the simulations using FEM will be imperative for the reliability of models used in practical applications. Advanced materials and surface coatings might further enhance wear resistance as well as fatigue life. In addition, with the combination of FEM with other analytical techniques like fracture mechanics and fatigue analysis, it can provide a more holistic view of the issue concerning the propagation of defects and failure mechanisms. Additionally, knowledge of manufacturing defects such as surface roughness and residual stresses shall inform quality control practices for designs to be more reliable gear systems.

References

[1] M. A. Khan et al., “Gear misalignment diagnosis using statistical features of vibration and airborne sound spectrums,” Measurement, vol. 145, pp. 419–435, 2019.

[2] K. Kishore, A. Sharma, and G. Mukhopadhyay, “Failure analysis of a gearbox of a conveyor belt,” Journal of Failure Analysis and Prevention, vol. 20, pp. 1237–1243, 2020.

[3] W. Feng, Z. Feng, and L. Mao, “Failure analysis of a secondary driving helical gear in transmission of electric vehicle,” Engineering Failure Analysis, vol. 117, p. 104934, 2020.

[4] A. Parey, N. Jain, and S. Koria, “Failure analysis of air cooled condenser gearbox,” Case Studies in Engineering Failure Analysis, vol. 2, no. 2, pp. 150–156, 2014.

[5] P. Manda, S. Singh, and A. Singh, “Failure analysis of cooler fan drive gear system of helicopter,” Materials Today: Proceedings, vol. 5, no. 2, pp. 5254–5261, 2018.

[6] M. Lias, T. Rao, M. Awang, and M. Khan, “The stress distribution of gear tooth due to axial misalignment condition,” Journal of Applied Sciences, vol. 12, no. 23, pp. 2404–2410, 2012.

[7] T. Loutas, D. Roulias, E. Pauly, and V. Kostopoulos, “The combined use of vibration, acoustic emission and oil debris on-line monitoring towards a more effective condition monitoring of rotating machinery,” Mechanical systems and signal processing, vol. 25, no. 4, pp. 1339–1352, 2011.

[8] E. Y. Salawu, O. O. Ajayi, and A. Inegbenebor, “Forensic investigation of a failed intermediate starwheel spur gear tooth in a filler machine,” Procedia Manufacturing, vol. 35, pp. 97–102, 2019.

[9] Y. Yu, J. Shi, C. Shen, Y. Luo, T. Wang, and Z. Zhu, “Dynamic modelling of gearbox with multiple localized defects and its coupled vibration analysis,” Mechanical Systems and Signal Processing, vol. 180, p. 109469, Nov. 2022, doi: 10.1016/j.ymssp.2022.109469.

[10] S. K. Panda, P. K. Mishra, B. Patra, and S. K. Panda, “Static and dynamic analysis of spur gear,” International Journal of Hydromechatronics, vol. 3, no. 3, pp. 268–280, 2020.

[11] O. D. Mohammed and M. Rantatalo, “Gear fault models and dynamics-based modelling for gear fault detection – A review,” Engineering Failure Analysis, vol. 117, p. 104798, Nov. 2020, doi: 10.1016/j.engfailanal.2020.104798.

[12] X. Liu, H. Huang, and J. Xiang, “A personalized diagnosis method to detect faults in gears using numerical simulation and extreme learning machine,” Knowledge-Based Systems, vol. 195, p. 105653, 2020.

[13] S. A. Mohammed, N. M. Ghazaly, and J. Abdo, “Fault diagnosis of crack on gearbox using vibration-based approaches,” Symmetry, vol. 14, no. 2, p. 417, 2022.

[14] Y. Xu, G. Feng, X. Tang, S. Yang, F. Gu, and A. D. Ball, “A Modulation Signal Bispectrum Enhanced Squared Envelope for the detection and diagnosis of compound epicyclic gear faults,” Structural Health Monitoring, vol. 22, no. 1, pp. 562–580, 2023.

[15] A. A. Dubaish and A. A. Jaber, “State-of-the-art review into signal processing and artificial intelligence-based approaches applied in gearbox defect diagnosis,” Engineering and Technology Journal, pp. 1–16, 2023.

[16] M. A. Khan and A. G. Starr, “Theoretical and experimental working life comparison for a helical gear under linear pitting failure,” Applied Mechanics and Materials, vol. 7, pp. 95–100, 2007.

[17] X. Liang, H. Zhang, L. Liu, and M. J. Zuo, “The influence of tooth pitting on the mesh stiffness of a pair of external spur gears,” Mechanism and Machine Theory, vol. 106, pp. 1–15, 2016.

[18] P. Goswami and R. N. Rai, “A systematic review on failure modes and proposed methodology to artificially seed faults for promoting PHM studies in laboratory environment for an industrial gearbox,” Engineering Failure Analysis, vol. 146, p. 107076, 2023.

[19] Y. Qu, H. Zhang, L. Hong, Y. Tan, and Z. Zhou, “Dynamic Modeling and Fault Feature Analysis of Pitted Gear System,” in 2018 IEEE International Conference on Prognostics and Health Management (ICPHM), IEEE, 2018, pp. 1–8.