In Depth Analysis On Model Haviour Of Gear Wheels With Defects Under Static Conditions

A.V. Sanyasi Raju[1],P V V S Maneendra[2],V.Satyanarayana[3]
[1]M Tech (CAD/CAM) Student of Mechanical Engineering, Godavari Institute of Engineering & Technology, Autonomous, Rajamahendravaram, A.P, India.
[2] Faculty of Mechanical Engineering, Godavari Institute of Engineering & Technology, Autonomous, Rajamahendravaram, A.P, India.
[3] Faculty of Mechanical Engineering, Kakinada institute of Technology & science, Autonomous, Divili, A.P, India.

Abstract- *The supervision task of industrial systems is vital, and the prediction of damage avoids many problems. If any system defects are not detected in the early stage, this system will continue to degrade, which may cause serious economic loss. In industrial systems, the defects change the behaviour and characteristics of the vibration signal. This change is the signature of the presence of the defect. The challenge is the early detection of this signature.*

In this project we will study on the frequency signatures of gear wheels, with and without defects, under static conditions, this study will help us understand the model behaviour of a gear wheel with different defects, also we can address several issues like, shutdowns, breakdowns, etc., in the study.

First a 3D cad model of a dryer gear wheel is generated form a 2d Cad drawing, this particular component is being used industrially, the Cad model is then used to study for natural frequencies, under different defects, these work is done in Ansys, a fem based software, later the results are validated using experimentally calculated frequencies.

I. INTRODUCTION

Gears are fundamental components in mechanical systems, serving a crucial role in transmitting power and motion between rotating shafts. They are found in countless machines, from simple household devices to complex industrial machinery. In industrial applications, gear wheels (or gear systems) are indispensable for a wide range of mechanical operations, including those involving heavy-duty equipment, manufacturing processes, and transportation systems. These components are designed to transfer torque, adjust the speed of rotation, and change the direction of motion, making them integral to many industries.

In this section, we will explore the importance of gear wheels in mechanical systems, their role in power transmission, and their broader significance in industrial machinery. This comprehensive overview will help in understanding the criticality of maintaining gear systems in optimal condition and detecting defects at early stages to avoid failures and economic losses. Torque Transmission Gears are designed to transmit torque between rotating shafts. In most systems, the driving gear is connected to a power source, while the driven gear is connected to a load. Speed Adjustment One of the most important functions of gears is to adjust the speed of rotation. When gears of different sizes are meshed together, the speed of the driven gear changes in relation to the size ratio of the gears. For instance, if a smaller gear drives a larger gear, the speed of the driven gear is reduced, but the torque is increased. This principle is fundamental in machines where specific speed and torque outputs are required for optimal operation, such as conveyor belts, escalators, and wind turbines.

Direction of Motion: Gears can also change the direction of motion. For example, meshing two spur gears causes the driven gear to rotate in the opposite direction of the driving gear

Power Distribution In complex machinery, gear trains are often used to distribute power across multiple components. A single driving gear can power several driven gears

Mechanical Advantage Gears provide mechanical advantage by allowing machines to exert greater force than would be possible with direct power transfer alone. By adjusting the gear ratio, engineers can design systems that maximize efficiency while minimizing energy consumption.

GEAR MESHING FREQUENCY: One of the most critical aspects of gears is their ability to change the speed and torque of a rotating system through gear ratios. The gear ratio is the relationship between the number of teeth on two meshed gears. A higher gear ratio results in more torque and less speed, while a lower ratio increases speed but reduces torque. This flexibility in adjusting speed and torque is particularly important in industrial applications, where machines must perform different tasks requiring various levels of power.

In manufacturing Paper Industry, especially in Paper machine dryers are rotated with partial Gear trains (Open gear system).In this project , we will study on frequency signature analysis of Gear trains with and without defects under static and dynamic conditions. This study will help us to understand the Modal behaviour of Gear wheel with different defects like Broken teetk, Teeth wear , Misalignment and Unbalance conditions.Modal and Harmonic Response analysis using ANSYS workbench siftware.Modal analysis in Ansys used to study the behaviour of parts or assemblies under vibrations .

It is used vibration characterstics like Natural Frequencies and Mode shapes under different frequencies.Modal analsis is the prerequisite for Dynamic Harmonic response analysis. Each part in the Machinary has natural frequencey to vibrate under certain conditions and these are moved large enough to damage the parts under resonace frequencies. The purpose, why we are doing these analysis is that Gears will be in statis condition during Annual Shut downs for more more periods. Natural frequencies of gears (defectless and different defective gears) can be found our by Bump test during the static condition and utilized for comparing with Modal and dynamics analysis and for validation and future studies .First step to study 3D cad model is generated from 2D model. This component is used industrially , the cad model is then used to study for natural frequencies, under differen defects ,this work is done in fem based software and later the results will be validated.

Problem Statement: Systems play a crucial role in industrial machinery, ensuring smooth and efficient power transmission. However, undetected defects in these systems can lead to significant issues, including machine breakdowns, unscheduled shutdowns, and costly repairs. Defects such as cracks, tooth wear, pitting, and misalignment can deteriorate gear performance over time, eventually causing mechanical failure.

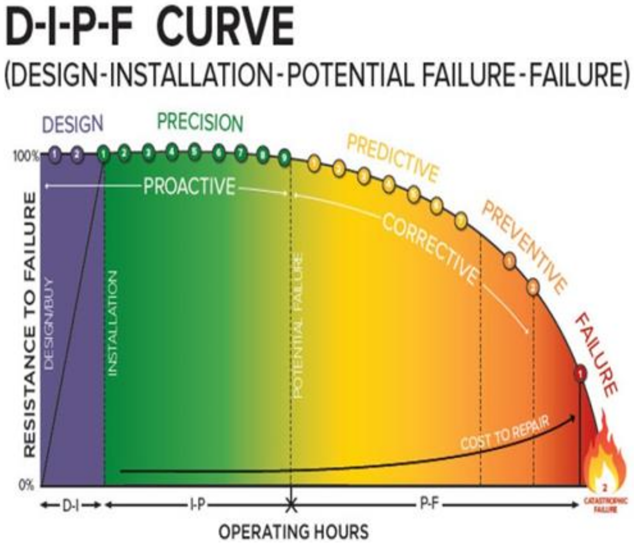
If these defects are not identified early, they can lead to catastrophic failures, resulting in substantial economic losses due to downtime, equipment damage, and the high cost of emergency repairs or replacements. One of the primary challenges is detecting early-stage defects, particularly under static conditions, when the system is not in motion.

Vibration analysis and other dynamic condition monitoring techniques are often effective at identifying defects in rotating systems, but detecting issues in stationary gears is more complex. Static condition monitoring typically involves analysing stress distribution and natural frequencies, which can be more subtle and harder to detect. This presents a significant challenge for maintenance teams, as early detection is critical to preventing failures. The ability to accurately model gear behaviour with defects under static conditions is vital for improving predictive maintenance strategies and minimizing the risk of unexpected breakdowns.

Objectives: The primary objective of this study is to analyze the behaviour of gear wheels with various defects under static conditions. Understanding how defects such as cracks, tooth wear, and misalignment affect gear performance when the system is not in motion is critical for early detection and predictive maintenance. By focusing on static conditions, we aim to identify subtle changes in gear behaviour that are often missed in dynamic analysis, enabling more effective condition monitoring.

Previous Studies on Gear Defects and Failure Detection

Gears are critical components in mechanical systems, and their performance can be significantly affected by various types of defects, such as cracks, pitting, wear, and misalignment. Detecting these defects early is vital to avoid system failures, nplanned downtime, and costly repairs. Over the years, numerous studies have focused on the vibration analysis of gears to detect these defects, as vibration-based techniques are considered highly sensitive to mechanical changes and disturbances caused by defects. For replacement of Gear in dryer system takes 16 hours and productivity loss is very high. Designing is very crucial role for gear manufacturing and finding the natural frequency is critical and behavior of gear produces at different defects at different frequencies.

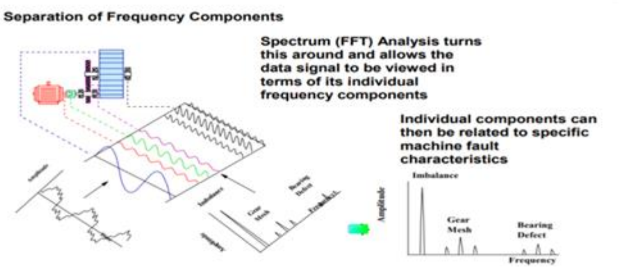

D-I-P-F CURVE
(DESIGN-INSTALLATION-POTENTIAL FAILURE-FAILURE)

Another key objective is to investigate the natural frequencies of gear wheels with and without defects. Natural frequency analysis provides insight into how defects alter the vibration characteristics of gears, which can serve as an early indicator of potential failures. By comparing the natural frequencies of intact gears to those with specific defects, we can pinpoint the impact of each defect type on overall gear performance. Lastly, the study seeks to validate the numerical findings from simulations using experimental results. The finite element method (FEM) will be used to simulate gear behaviour in software like ANSYS, and these simulations will be cross-checked against experimentally measured frequencies. This validation process is essential to ensure the accuracy of the numerical models and enhance their practical applicability in real-world industrial settings.

Vibration Analysis of Gears with Defects

Vibration analysis has emerged as one of the most widely used methods for monitoring the health of gear systems. By measuring the vibrations produced during gear operation, it is possible to identify patterns that correspond to normal operation as well as those that signal the presence of defects. When a gear tooth is damaged, for example, the meshing process between gears generates irregular vibrations that deviate from typical harmonic signatures. These deviations can be analyses to detect various types of defects, even at early stages.

Researchers have focused on understanding how different defects influence the vibration characteristics of gear systems. Early studies by McFadden and Smith (1984) were among the first to identify the connection between gear tooth defects and changes in the amplitude of vibration signals. They introduced methods for identifying the cyclic nature of gear vibrations and how defects like pitting and cracks cause modulation in the vibration signal. Later studies refined these approaches by using time-frequency domain analysis, which helped distinguish defect-related vibrations from noise.



Key Findings on Defect-Induced Changes in Vibration Signatures

A consistent finding in the literature is that specific defects cause unique changes in the vibration signatures of gear systems. Some of the key findings include:

CrackFormation:Cracks in gear teeth alter the stiffness of the gear mesh, leading to changes in the natural frequencies of the system. These cracks can also cause localized increases in vibration amplitude during the meshing process. Researchers have found that cracks are often associated with sideband frequencies in the vibration spectrum, making it possible to detect even small cracks before they grow large enough to cause failure.

Misalignment and Load Variation Misalignment between gears results in uneven distribution of forces across the gear teeth, leading to vibration patterns that deviate from normal operation. These patterns typically show up as changes in the amplitude and phase of the vibration signal at the fundamental meshing frequency. Misalignment can also cause increased wear and higher vibration levels over time, further exacerbating the defect's impact on gear performance.

Tooth Breakage A broken tooth creates a significant disturbance in the gear mesh, resulting in large spikes in the vibration signal. This defect is often accompanied by increased noise and a sharp rise in vibration amplitude. Studies have shown that broken teeth are easily detected due to the abrupt and substantial changes they cause in vibration patterns, making them one of the more straightforward defects to diagnose. Overall, vibration analysis has proven effective in identifying a wide range of defects in gear systems, particularly in dynamic conditions where the gear is in motion. However, its application to static conditions, where the system is not operating, remains more limited, as discussed in the following section.

In this project we will study on the frequency signatures of gear wheels, with and without defects, under static conditions, this study will help us understand the model behavior of a gear wheel with different defects, also we can address several issues like, shutdowns, breakdowns, etc., in the study first a 3D cad model of a dryer gear wheel is generated form a 2d Cad drawing, this particular component is being used industrially, the Cad model is then used to study for natural frequencies, under different defects, these work is done in Ansys, a fem based software, later the results are validated using experimentally calculated frequencies. In present industrial scenario, our target is to achieve maximum production with minimum down time. In olden days, Maintenance philosophies used to follow are Break down maintenance are preventive (basing on Time Interval). Now a days, to achieve the highest productivity, Predictive / condition based maintenances maintenance and proactive maintenance (conducting Root cause failure analysis) are inevitable to detect and correct from design to redesign stage in addition to attend precision maintenance procedures like

Laser alignment , static and dynamic balancing of rotating parts and following best assembling procedures to mechanical equipment’s and with high quality lubrication procedures like Wear debris analysis and oil cleaning procedures in a professional way. With reference to D-I-P-F Curve , Design and installation is in static and Installation to failure will be in Dynamic stage.

Static vs. Dynamic Condition Studies: Most research on gear defect detection has focused on dynamic conditions, where gears are rotating and transmitting power. In these conditions, vibration analysis and other monitoring techniques can capture real-time data on the performance of the system, making it easier to identify changes in behaviour due to defects. However, fewer studies have explored gear behavior in static conditions, despite the fact that many gear systems are in a static state for significant periods during maintenance, shutdowns, or standby modes.

Gear Behavior in Dynamic Conditions: Under dynamic conditions, the rotation of the gear system generates vibrations due to the interaction of gear teeth during meshing. The frequency and amplitude of these vibrations are directly related to the condition of the gears. In healthy gears, the vibrations follow predictable patterns, with well-defined frequencies known as the gear meshing frequency (GMF) and its harmonics. Defects disrupt this pattern, resulting in changes that can be detected through various analytical techniques such as Fourier analysis, wavelet transforms, and envelope detection.

Dynamic condition studies have demonstrated that even minor defects can be detected through vibration analysis if the system is sufficiently sensitive. For example, a study by Amaranth et al. (2013) demonstrated that gear tooth cracks as small as 10% of the tooth width could be identified using vibration-based methods. This ability to detect small defects early is critical for preventing catastrophic failures in industrial systems.

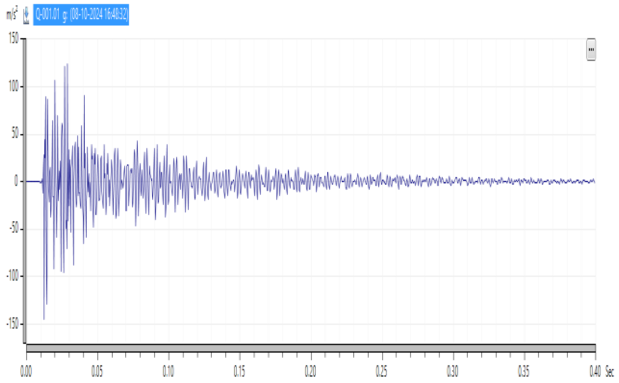
Gear Behavior in Static Conditions:In contrast, gear systems under static conditions do not produce vibrations because they are not rotating or transmitting power. This makes defect detection more challenging, as many of the traditional methods used in dynamic analysis are not applicable. Instead, researchers must rely on other techniques, such as stress analysis, natural frequency analysis, and modal testing, to identify defects in static gears.

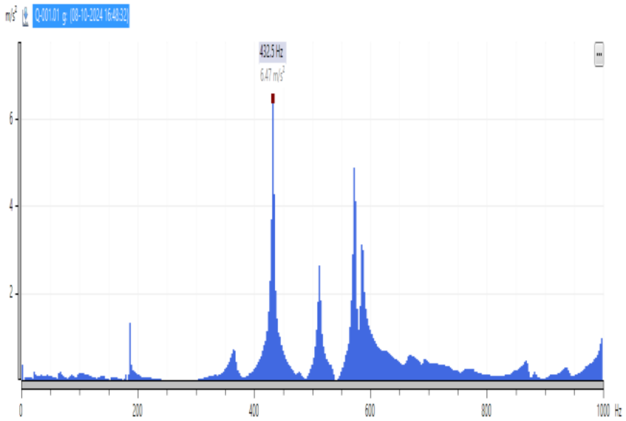
One of the main difficulties in studying static conditions is the subtlety of the changes caused by defects. While cracks and other defects can affect the stiffness and structural integrity of the gear, these changes are often small and difficult to detect without advanced analytical tools. Furthermore, the absence of rotational motion means that defects may not manifest in easily measurable ways, such as changes in vibration amplitude.

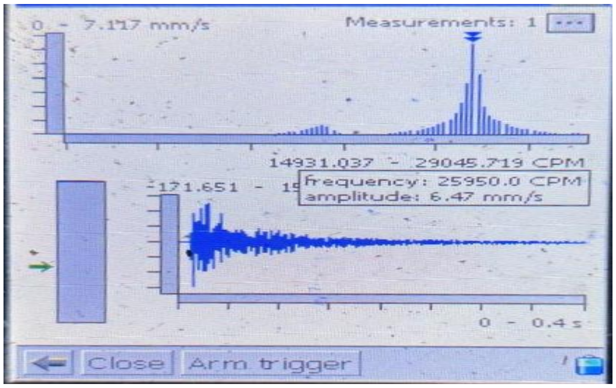
Gaps in Existing Research on Static Condition Defect Detection: Although there has been significant progress in detecting gear defects under dynamic conditions, there is a noticeable gap in the research on static condition detection. Most existing studies have focused on how gears behave during operation, leaving a gap in understanding how defects affect gears when they are not in motion. The main challenge lies in the fact that static analysis requires different techniques and approaches compared to dynamic analysis, and these techniques have not been as extensively developed.

For example, while natural frequency analysis can be used to detect changes in the vibration properties of a gear due to defects, this method is often less sensitive than dynamic vibration analysis. Additionally, experimental validation of static condition models is more difficult because the absence of motion makes it harder to replicate real-world conditions in a laboratory setting.

PERFORMED BUMP TEST TO KNOW THE NATURAL FREQUENCY OF THE GEAR WHEEL ON 08-10-2024 AT RJ#3 MACHINE-ANDHRA PAPER LIMITED RAJAMAHENDRAVARAM







Techniques for Defect Detection in Gears Several methods have been developed to detect defects in gear systems, ranging from numerical simulation techniques like Finite Element Method (FEM) analysis to experimental and vibration-based techniques. Each method has its strengths and limitations, and the choice of technique often depends on the specific conditions and requirements of the application.

FEM Analysis Finite Element Method (FEM) analysis is a numerical simulation technique used to model the behaviour of gear systems under various loading and boundary conditions. FEM is particularly useful for studying the structural integrity of gears, as it allows for detailed analysis of stress distribution, deformation, and natural frequencies. When applied to gear defect detection, FEM can simulate the impact of defects such as cracks, wear, and misalignment on the performance of the gear. In FEM analysis, the gear system is divided into small elements, and the equations governing the mechanical behaviour of these elements are solved to determine how the system as a whole responds to different conditions. This makes FEM an ideal tool for investigating the effects of defects under both static and dynamic conditions. For example, researchers can use FEM to model how a crack in a gear tooth affects the stress distribution in the gear and how this change in stress alters the gear's natural frequencies. One of the key advantages of FEM is its ability to simulate a wide range of defects and conditions, making it a versatile tool for gear defect analysis. However, FEM simulations are often time-consuming and computationally intensive, especially for complex systems with multiple gears or non-linear interactions.

Vibration-BasedTechniques

Vibration-based techniques are among the most widely used methods for detecting gear defects, particularly under dynamic conditions. These techniques involve measuring the vibrations produced by the gear system during operation and analyzing the resulting signal to identify changes that correspond to defects. The most common vibration-based techniques include:

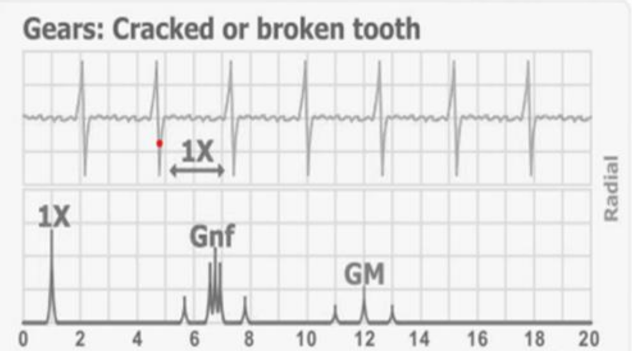
Fourier Transform Analysis: Converts time-domain vibration signals into the frequency domain, making it easier to identify changes in the gear meshing frequency and its harmonics caused by defects.

Experimental Methods: Experimental methods for gear defect detection typically involve testing the gear system in a controlled laboratory setting to measure its performance under different conditions. These methods often include modal testing, where the natural frequencies and mode shapes of the gear are measured to identify changes caused by defects. In addition, acoustic emission testing can be used to detect high-frequency noise generated by defects, particularly in static conditions. Bump test also ready explained.

Experimental methods are valuable for validating numerical models and simulations, such as those produced by FEM analysis. However, they can be costly and time-consuming to set up, and they may not always replicate real-world operating conditions accurately.

The literature on gear defect detection has provided valuable insights into how defects such as cracks, pitting, and wear affect the performance of gear systems, particularly under dynamic conditions. Vibration-based techniques have proven highly effective at detecting these defects early, but there is still a significant gap in.

AREA : RJ#3 NAME : 2ND GROUP LINE SHAFT DRYER-10 GEAR

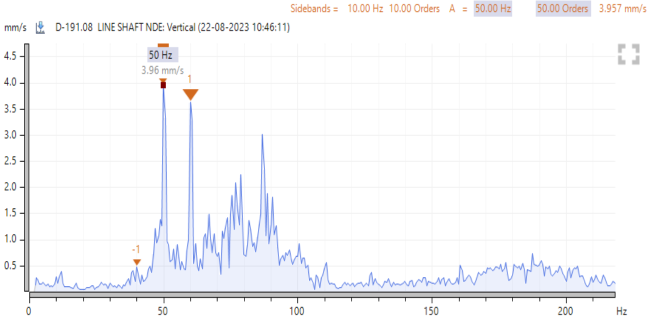


Cracked or broken teeth: -

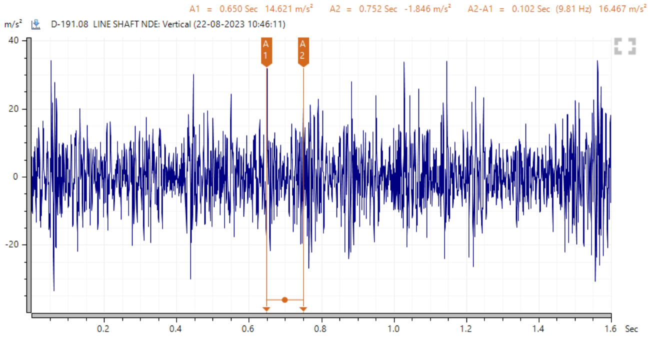
A cracked or broken tooth generates a high amplitude peak art the turning speed of that gear and its will cause the gear natural frequency to be exited. There will be sidebands of turning speed of that gear around gear mesh frequency.

However, the best way to see a cracked or broken tooth is in the waveform. If there were 12 teeth, one of 12 pulses in the waveform will be very different from the others. The time difference between these pulses will be equal to the period of the turning speed of the gear because the tooth comes into contact once per revolution

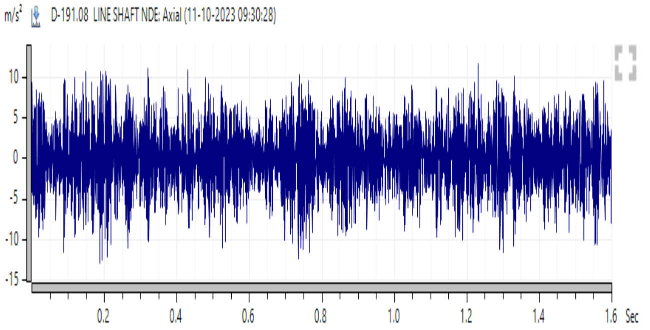
Before gear wheel change vibration spectrum



Before gear wheel change time wave form



After gear wheel change vibration spectrum



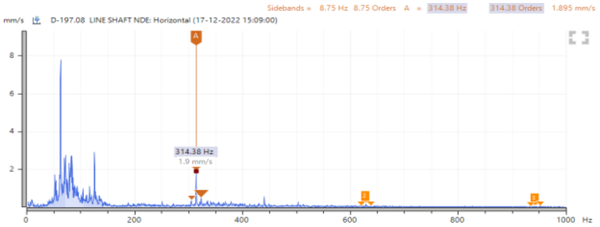
AREA : RJ#3 NAME : 7th GROUP LINE SHAFT DRYER-38 GEAR

Tooth wear: - When teeth begin to wear, two things will happen. The first is that the sidebands of gear mesh will increase in levels. The side bands will correspond to the speed of the gear with the wear. The side bands will develop as a result of amplitude or frequency modulation.

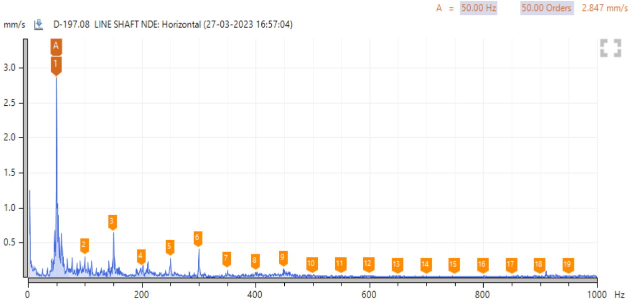
The second thing that occurs is that the natural frequency of the gear is excited due to the impacting of the gears meshing. This peak will also exhibit sidebands, and as a natural frequency, it is likely to have a broader base.

The 3X gear mesh frequency will increase in amplitude and multiple side bands will appear.

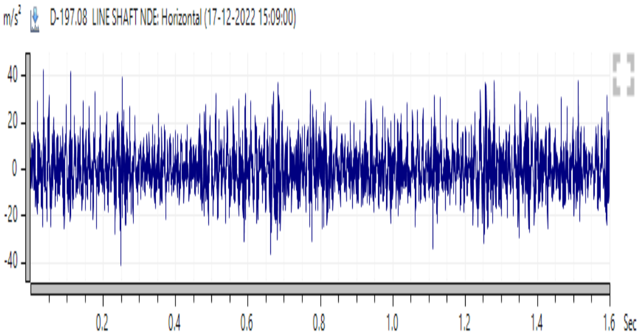
After gear wheel change vibration spectru



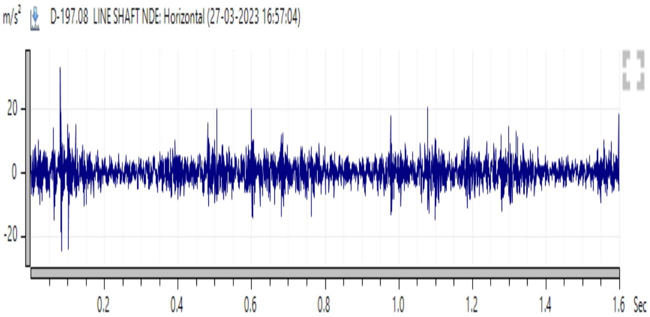
After gear wheel change time wave form



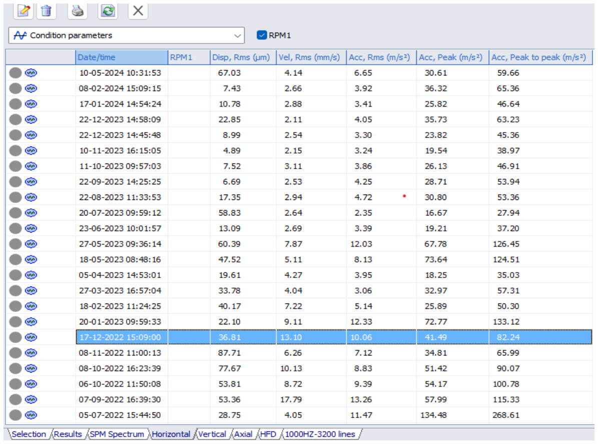
before gear wheel change time wave form



After gear wheel change time wave form



Conversion of MPM to RPS



Date/time	RPM1	Disp, Rms (µm)	Vel, Rms (mm/s)	Acc, Rms (m/s²)	Acc, Peak (m/s²)	Acc, Peak to peak (m/s²)
10-05-2024 10:31:53		67.03	4.14	6.65	30.61	59.66
08-02-2024 15:09:15		7.43	2.66	3.92	36.32	65.36
17-01-2024 14:54:24		10.78	2.88	3.41	25.82	46.64
22-12-2023 14:58:09		22.85	2.11	4.05	35.73	63.23
22-12-2023 14:45:48		8.99	2.54	3.30	23.82	45.36
10-11-2023 16:15:05		4.89	2.15	3.24	19.54	38.97
11-10-2023 09:57:03		7.52	3.11	3.86	26.13	46.91
22-09-2023 14:25:25		6.69	2.53	4.25	28.71	53.94
22-08-2023 11:33:53		17.35	2.94	4.72	30.80	53.36
20-07-2023 09:59:12		58.83	2.64	2.35	16.67	27.94
23-06-2023 10:01:57		13.09	2.69	3.39	19.21	37.20
27-05-2023 09:36:14		60.39	7.87	12.03	67.78	126.45
18-05-2023 08:48:16		47.52	5.11	8.13	73.64	124.51
05-04-2023 14:53:01		19.61	4.27	3.95	18.25	35.03
27-03-2023 16:57:04		33.78	4.04	3.06	32.97	57.31
18-02-2023 11:24:25		40.17	7.22	5.14	25.89	50.30
20-01-2023 09:59:33		22.10	9.11	12.33	72.77	133.12
17-12-2022 15:09:00		36.81	13.10	10.06	41.49	82.24
08-11-2022 11:00:13		87.71	6.26	7.12	34.81	65.99
08-10-2022 16:23:39		77.67	10.13	8.83	51.42	90.07
06-10-2022 11:50:08		53.81	8.72	9.39	54.17	100.78
07-09-2022 16:39:30		53.36	17.79	13.26	57.99	115.33
05-07-2022 15:44:50		28.75	4.05	11.47	134.48	268.61

	V= πdn/1000				1 X DRYER RPM	2 X DRYER RPM	3 X DRYER RPM	1 X GMF OF GEAR AND PINION	2 X GMF OF GEAR AND PINION	3 X GMF OF GEAR AND PINION	1 X GMF OF GEAR RPM AND PINION TEETH	2 X GMF OF GEAR RPM AND PINION TEETH	3 X GMF OF GEAR RPM AND PINION TEETH
MPM	RPM	CONVERTION TO FREQUENCY	GEAR TEETH	PINION TEETH	RPM IN Hz	RPM IN Hz	RPM IN Hz	GMF	GMF	GMF	2ND STAGE GMF	2ND STAGE GMF	2ND STAGE GMF
400	84.85	60	180	35	1.41	2.83	4.24	254.55	509.09	763.64	49.49	98.99	148.48
440	93.33	60	180	35	1.56	3.11	4.67	280.00	560.00	840.00	54.44	108.89	163.33
480	101.82	60	180	35	1.70	3.39	5.09	305.45	610.91	916.36	59.39	118.79	178.18

Generation of a 3D CAD Model of a Dryer Gear Wheel from 2D Drawings

The first step in the design and simulation approach is the development of a highly accurate 3D model of the gear wheel. This process begins by converting 2D technical drawings of the gear wheel into a 3D model using CAD (Computer-Aided Design) software. In this study, SolidWorks is used as the primary software tool to create the 3D model, which is then used for further analysis. SolidWorks is well-suited for this task due to its robust features for parametric design, ease of use, and powerful

Simulation of Defective and Non-Defective Dryer Gear Wheels Once the 3D model of the dryer gear wheel is completed, it is used for a series of simulations to study the behavior of the gear under different conditions, particularly in the presence of defects. The simulation process is carried out using FEM-based software such as ANSYS, which allows for detailed analysis of stress distribution, deformation, and natural frequency changes caused by defects.

Stress Analysis The first set of simulations involves applying static loads to the gear model to analyze how the stresses are distributed across the gear teeth. These simulations help identify areas of the gear that are most prone to failure, such as the tooth root, where stress concentrations are typically highest. Defective models (e.g., models with cracks or wear) are compared to non-defective models to observe how these defects alter the stress distribution.

Natural Frequency Analysis Another important aspect of the simulation is natural frequency analysis. The presence of defects can alter the stiffness of the gear system, which in turn affects its natural frequencies. By simulating the gear wheel with and without defects, changes in the natural frequencies can be identified, providing insight into how defects impact the overall vibrational behavior of the gear.

Modal Analysis Modal analysis is performed to study the vibrational modes of the gear wheel. Understanding the mode shapes and frequencies is critical for predicting how the gear will respond to dynamic forces, especially when defects are present. Defective gear wheels often exhibit shifts in their modal frequencies and altered vibrational modes, which can be used to detect the presence of cracks, pitting, or other structural issues.

Fatigue Life Prediction Fatigue life prediction simulations

In this study, the Finite Element Method (FEM) is utilized through ANSYS, a powerful engineering simulation software, to simulate the behavior of a gear wheel under static conditions. The main goal is to understand how various defects impact the natural frequencies of the gear and to evaluate the structural integrity of the component

Identifying Natural Frequencies in Gears with and without Defects

The simulation aims to identify the gear's natural frequencies, which indicate how the gear will resonate under operational conditions. The presence of defects such as cracks, broken teeth, or misalignment alters the stiffness and mass distribution, leading to changes in the natural frequencies. By comparing these frequencies in defective and non-defective gears, it is possible to detect abnormalities early

Modal analysis is used to identify the natural frequencies of the gear system for different wear percentages. These frequencies indicate how the gear responds to vibrational forces and can highlight how defects or wear affect the resonance of the system.

Natural Frequencies: As the wear percentage increases, the natural frequencies of the gear system also increase slightly. For instance, in the first mode, the frequency rises from 60.312 Hz at 0% wear to 63.063 Hz at 50% wear. Similar trends are observed in other modes, with higher frequencies occurring at higher wear levels. This increase in natural frequency can be attributed to the stiffening of the system due to the material loss. When the gear loses material, especially at the tooth surface, the mass of the gear decreases, which results in higher frequencies.

For higher modes, the frequency changes become more pronounced. For example, the 14th mode frequency increases from 407.56 Hz at 0% wear to 431.43 Hz at 50% wear. This highlights the increasing stiffness of the gear with more wear, which shifts the resonance to higher

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.

Displacement Amplitude:

The displacement amplitude shows a noticeable decrease with increasing wear. For example, the maximum displacement at 0% wear is 0.12412 mm, while it drops to 4.45E-03 mm at 50% wear. This trend indicates that as wear increases, the gear becomes stiffer, resulting in lower displacement amplitudes under harmonic excitation. The reduced material at higher wear percentages makes the gear less flexible and able to deform less under dynamic loads.

Natural Frequencies: The increase in natural frequencies with wear suggests that the gear becomes more prone to higher-frequency vibrations, which may shift its resonance behaviour. While this might reduce the risk of low-frequency resonance, it could expose the gear to higher-frequency excitations, which could lead to fatigue or failure if operating near those frequencies.

Dynamic Condition Analysis: Implementing dynamic condition analysis is essential for a comprehensive understanding of gear performance. This involves simulating gear systems under varying operational loads and conditions, capturing the complexities of gear interactions and how they evolve over time. Such analysis can help identify resonance phenomena, transient responses, and other dynamic behaviours that static studies may miss.

Real-Time Monitoring Techniques: Developing and integrating real-time monitoring techniques, such as vibration analysis, acoustic emission sensors, and temperature monitoring, will enhance predictive maintenance strategies. These technologies can provide continuous feedback on the health of gear systems, allowing for timely interventions and preventing catastrophic failures.

Integration of Machine Learning: Future research could explore the integration of machine learning algorithms to analyze data collected from real-time monitoring. By leveraging historical data and identifying patterns in gear behavior, machine learning can improve predictive maintenance models, leading to more accurate predictions of when maintenance is required.

Experimental Validation: To further validate the findings from static and dynamic analyses, experimental studies should be conducted on actual gear systems. This will provide a more realistic assessment of gear performance and the impacts of wear and defects under operational conditions.

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