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A STUDY OF BOTH TRADITIONAL AND ANN VIBRATION-BASED GEAR DEFECT MONITORING AND PREDICTION SYSTEMS

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ABSTRACT

A gearbox is an essential component of many mechanical transmissions of power used in several industrial applications, such as wind turbines, automobiles, material handling and mining equipment, offshore vessels, aeroplanes and oil and gas processing equipment. Gear wear, an inherent event during gear service, diminishes the gear gearbox system's remaining useful life and compromises the durability of the gear tooth. The progression of gear wear may result in serious gear malfunctions including tooth breaking and gear root cracks, which can further result in dangerous situations or unplanned equipment shutdowns. For this reason, monitoring the spread of gear wear is necessary to perform predictive maintenance. When diagnosing localized failures like gear root cracks and tooth surface spalling, vibration analysis is a commonly used and efficient method for keeping an eye on the performance of rotating machinery. Given that both gear faults and variations in the gearbox's load are important causes of vibration in gearboxes, an early fault identification of the gearbox can be accomplished by analyzing the vibration signal using a variety of signal processing techniques. This review paper will perform a thorough review on vibration-based gear wear monitoring. This will involve examining the various gear wear mechanisms that result in different gear surface features, Analyzing the relationship between gear surface features and vibration characteristics, and providing an overview of the research on vibration-based gear wear monitoring. The suggested indications are not only useful for monitoring gear wear, but they can also be used as general criteria to find additional problems such tooth cracks or shaft misalignments, which alter the vibrations of the gears.

Keywords: Gearbox, Vibration analysis, Wear monitoring.

1. INTRODUCTION

As gearboxes have numerous advantages, such as compact structures, stable gearbox capability, and low noise, they have been widely used in a variety of diligence, such as energy from renewable sources, high-tech manufacturing, vehicle, mining, the aerospace industry, material running, oil paintings and gas, and power assiduity. Gear wear and tear is a gradual material loss caused by the relative movement of the entrapping tooth face. It's an ordinary and unavoidable occurrence during the service life of a piece of equipment [2]. Figure 1 depicts some common gear wear and tear forms such as scuffing, pitting, and wear. Gears are a major component of a machine's gearbox system, and proper gear system conservation is critical to ensuring the machine's performance. As gear wear and tear increases, the gear face becomes less continuous, the engaging gears' contact lubricants deteriorate, disunion and noise levels rise, and stress attention conforms. Additional types of failure, including gear cracks as well as gear tooth failures, may also be brought on by these effects, and these could result in major accidents, unplanned financial losses, or even an unexpected gear gearbox system arrest [3]. For instance, lubrication oil painting may become contaminated and the disintegration within the engaging gears may increase in a wind turbine due to gear wear and tear. This could increase the possibility of gear damage and cause the gearbox system of wind turbines to abruptly stop. Typically, wind turbines are built atop hills in cleared spaces. Consequently, the gearbox conservation process could take a few weeks or even months. As a result, wind turbines' electricity output would cease, resulting in a loss of electricity as well as financial loss. Another essential component of the vehicle's gearbox system is the gearbox. Transmission performance would be negatively impacted by gear wear and tear. Severe gear defect and tear could potentially lead to catastrophic accidents by destroying the entire gearbox system. Thus, it is crucial to cover and anticipate the spread of gear wear and tear in order to enhance the overall functionality and health of gearbox systems [1].

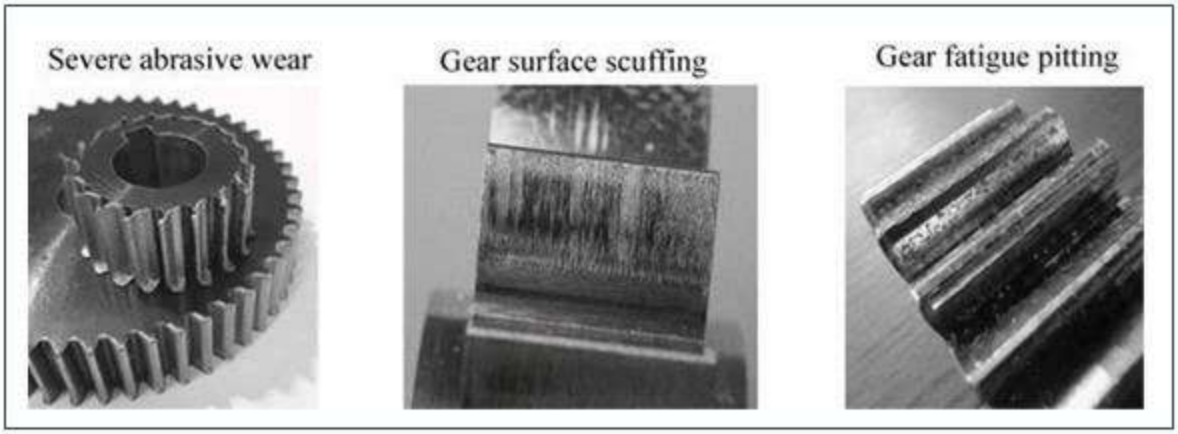

Figure 1: Gear wear patterns

Observing the condition of a gearbox is an important effort because of its importance in power transfer in any assiduity. Thus, there has been an ongoing bid for improvement in the monitoring methods for balancing the gear rates inside the gear box and the current that passes through the motor driving the gearbox. Inordinate vibration is a major cause of gear faults. The rate at which forces are applied to a gear in relation to its dynamic stiffness is known as vibration. The counters reaction, the gear gearbox error, the unsteady indolence mass, the tooth's time-varying mesh stiffness, the disunion between the tooth faces, and the geared system's time-varying support stiffness all alter the rate of vibration, which can be interpreted as a sign of a variety of defects or blights [4]. Since its inception, the effectiveness of analysis of vibration for gear monitoring of condition and the views has been proven due to its ease of dimensioning. Based on the analysis disciplines, there are three main orders of approach for gear vibration analysis. The three are called the time, frequency, and time-frequency spheres as well. Progressive material loss that results from rolling and sliding together on combined or boundary lubrication circumstances, leading to tooth shell wear, is referred to as gear wear and tear. It's just one of the main reasons gears fail. High vibration and noise levels, power transfer losses, and dynamic transmission errors are all direct consequences of gear wear and tear. Inequitable cargo distributions resulting from severe damage may also give rise to different kind of gear failure, such as broken teeth. As a result of these factors, the condition monitor community is paying close attention to the content of gear defect. Wear flyspeck analysis has been used extensively in practice to monitor gear wear and tear, while vibration evaluation techniques have been used only to monitor and provide an opinion on gear defects, not to investigate wear and tear. There has been theoretical investigation into how wear and tear affects gear dynamic features [9].

It has been acknowledged that the dynamic contents and its distribution are significantly impacted by tooth face damage. The gear rate of transmission will no longer remain stationary due to the alterations in the tooth's working face brought on by wear and tear, particularly in cases of spur gears, who's transmission crimes are highly susceptible to wear. Because the dynamic features of the gear may also affect the wear and tear process, there is a reciprocal relationship between them. Thus, it follows that changes in vibration characteristics would be the result of gear damage, and as a result, a vibration analysis- based method of gear defect monitoring should be able to be created. The state-of-the-art techniques for gear diagnostics rely on the analysis of vibration signals that are picked up by the gearbox cover. The common goal is to describe the existence and kind of fault at the initial stage of the development and to covers its elaboration in order to determine an appropriate conservation plan and estimate the machine's remaining life. It is commonly known that sidebands from modulation marvels and the tooth- entrapping frequency and its harmonics play a major role in gear vibration gaps. A fault condition could be indicated by the abundance of similar sidebands in both number and width. Additionally, the sidebands' source and distance are related.

The diagnostic use of vibration analysis for common gear failures such as tooth face chipping, gear cracking, and gear breaking is well-developed and widely implemented. A number of review papers, ranging from dynamic modeling to gear prophecies, were released to represent the vibration- grounded evaluation approaches for common gear failures. On the down side, there hasn't been much research done on vibration-grounded gear wear and tear monitoring, but the research community and diligence practices are starting to pay more attention. Nevertheless, there isn't presently a comprehensive analysis that outlines the evolution of vibration-grounded gear damage monitoring. An improved grasp of the mechanisms and features of gear wear and tear decline can be helpful to experimenters and masterminds in order to guarantee the safe functioning of the gearbox system. This understanding can lead to the formulation of prophetic conservation-based opinions. This paper aims to fill this void in the investigation. Gear dynamics and gear face wear and tear are intricately entwined, and this commerce presents challenges for vibration- grounded analysis. It has been acknowledged that during the progression of gear wear and tear, the dynamics of cargo and its distribution will change. The wear and tear-induced alteration to the tooth face would cause the gear system's gearbox rate to become irregular. This would be particularly problematic for spur gearbox methods, whose dynamical responses and gearbox crimes are highly susceptible to wear. Additionally, a system of gears vibration characteristics would undergo significant changes [7].

The goal of this review paper is to comprehensively examine and characterize how vibration characteristics are affected by different wear and tear mechanisms in gears. Initially, the gear defect way is introduced along with the effects it has on the revision of the gear tooth profile. In addition, by examining the interrelationships between the gear face characteristics and vibration characteristics, the live workshop on monitoring gear wear and tear is reviewed and exemplified from the perspectives of modelling and signal processing. The wear prediction techniques for typical wear phenomena are then reviewed and discussed. This review article provides a thorough overview of the advancements in vibration-based gear defect detection and forecasting techniques, covering everything from the fundamental causes of gear wear to wear propagation prediction methods [8].

2. Gear Wear

Gear failure is frequently caused by bending fatigue, wear, rupturing, scratching, spalling, and root cracks. Different classification schemes have been applied to gear failure modes. A few common tear and wear modes for gears will be covered in this section. [7] In order to provide further information, a list of tear and wear types from various transnational norms will be provided in order to illustrate various groupings. Also examined and illustrated will be the effects of gear wear and tear on the gear tooth face. Note that the introduction to a number of common gear wear and tear types is not meant to provide an additional gear defect and tear type bracket; rather, it is meant to aid compendiums in better understanding the common mechanisms of wear and tear in artificial operations. [12]

2.1Typical Gear Wear Modes

Throughout the gear's service life, surface wear is a common and inevitable occurrence. When under stress, gear pairs which mesh allows the tooth's flanks to stay in contact. A mix of roller and sliding motions is used to shift the tooth surfaces. The sliding component is visible where the two contacting teeth have different surface velocities. Decrease in gear mass, also known as gear wear, can result from material being lost from the teeth of the gear due to the sliding motion. Below is an overview of a number of typical wear mechanisms that affect the gearing system in industrial settings. The emphasis on the categorization of the gear wear methods is noteworthy. [12]

Classification of Gear Wear:

- Abrasive wear
- Fatigue pitting
- Adhesive wear
- Corrosive wear

Abrasive Wear:

Particle contamination-induced sliding contact or the lack of lubrication can lead to abrasive wear. The gear tooth geometrical profile is changed by radial scratches on the gear surface caused by abrasive wear. Two distinct forms of abrasive wear are two-body and three- body abrasives. Hard particles trapped within two sliding surfaces cause three-body abrasive wear, whereas two- body abrasive wear is produced when a rough, hard surface rubs against a softer surface. This review article addresses a number of research issues, including three- body abrasion wear, and this will be covered in greater detail in the following sections. This is so because the same materials are typically used to manufacture the mechanisms that engage gears inside a gear gearbox system**.**

Fatigue Pitting:

Cycle loading conditions give rise to a common surface fatigue phenomenon known as "fatigue pitting," which can result in fatigue fracture on the surfaces or subsurface of the gear teeth. Usually, the first crack propagates briefly within a path almost identical to the tooth's surface before twisting or branch to the gear's tooth surface. When a fatigue crack stretches to a stage where it separates part of a surface materials from the gear tooth, that is when fatigue pitting is officially created. The outcome of fatigue cracking propagation is defined in this study as fatigue pitting, more especially mechanical pitting. As a result, fatigue pitting, as covered in this study, is distinct from pitting rust and electrical pitting.

Adhesive Wear:

Gear teeth adhere to one another because of the material that is transferred from one gear's tooth surface to the next as a result of ripping.

Corrosive Wear:

Corrosion wear is one kind of wear that becomes apparent when the surface of the gear tooth ages. The reactions with the active components of the lubricant, whether chemical or electrochemical, are the main cause of it. Severe pressure from contact additives along with additional lubricant additives intended to prevent scuffing are frequent reasons why gear pairs experience moderately corrosive wear. When taken individually or in combination, the principal wear phenomena in machinery coated by the aforementioned wear phenomena probably account for approximately 95% of the wear that occurs within modern machinery. However, during the gearbox systems service life, a number of additional wear kinds, including as erosion, impact chopping, finishing, fretting, scaling, a cavity, and electrical discharge, may transpire.

3. EFFECTS OF WEAR ON GEAR VIBRATION SIGNALS

Most people agree that the main source of vibratory excitation in gear systems is gearbox error (TE). Elastic deformations of the tooth (elastic bending of the entire tooth and deformation due to elastic forces in the contact region) and geometrical deviations of the unloaded surfaces of operation from equip-spaced idealized involute profiles make up the TE under loaded conditions.

Depending on the rotating angle, a gear with N teeth may exhibit various variations in each tooth with respect to the optimum tooth profile, causing TE to fluctuate. As stated in, an average working surface variation from an ideal involute surface is the arithmetic mean of all these N working region variances. There are two of these average working surface deviations for a meshing gear pair, and the superposition of these results in teeth meshing harmonics in the vibration signal spectrum.

At the rotational speed of each gear, tooth-to-tooth variations are dispersed throughout the tooth meshing harmonics. These variances are made up of the differences between the average working surfaces deviation and the working surface deviations of individual teeth. A vibration spectrum with dual set of sideband, one for each gear, will be present if the tooth counts of the gears in a meshing pair differ.

When examining the effect of gear wear on TE, one can comprehend how it influences vibration signals. Variations in both TE and vibration signals are primarily caused by gear wear if the operating conditions of the gear and the gear supporting framework remain unchanged. According to the wear pattern, there will be variations in the standard working surface deviation along with the tooth-to-tooth variances.

Clothing is usually divided into two categories: uniforms and non-uniforms. When teeth are worn uniformly, or in the same direction, this is known as an ideal wear pattern. This kind of gear wear increases average working surface deviations and causes tooth meshing harmonic amplitudes to climb. Keep in mind that these tooth meshing harmonics' relative fluctuations are affected by the modification of an average working surface deviation. For example, the normal double-scalloped wear pattern will primarily result in an increase in the tooth meshing frequency's second harmonic. A problem known as non-uniform wear occurs when each tooth wears differently. Unlike homogenous wear, it will affect both the standard working surface deviations and the tooth-to-tooth variations. Tooth-to-tooth discrepancies can vary in magnitude depending on the situation. For instance, the tooth surface flaws are removed during the run-in of a pair of gears to improve conformance and reduce vibrations.

The dynamic reaction of the gear system and the gear wear cycle interact in complex ways. Generally speaking, gear wear may cause a reduction in the contact area or a modification to the shape of the gear tooth profile. This modifies the gear system's meshing stiffness and geometric gearbox error (GTE), which in turn affects the gear system's dynamic characteristics, such as the dynamic impact force and its distribution. This results in increased noise and vibration levels. The gear wear mechanism may be modified and accelerated as a result of the shift in dynamic contact force. It is especially difficult to keep an eye on the intricate dynamic response and vibration characteristics brought about by the dynamic interaction among gear surface wear and gear dynamics. This is particularly evident when contrasted with other malfunctions such as tooth breakage, gear root cracking, and tooth surface cracking. [6-10]

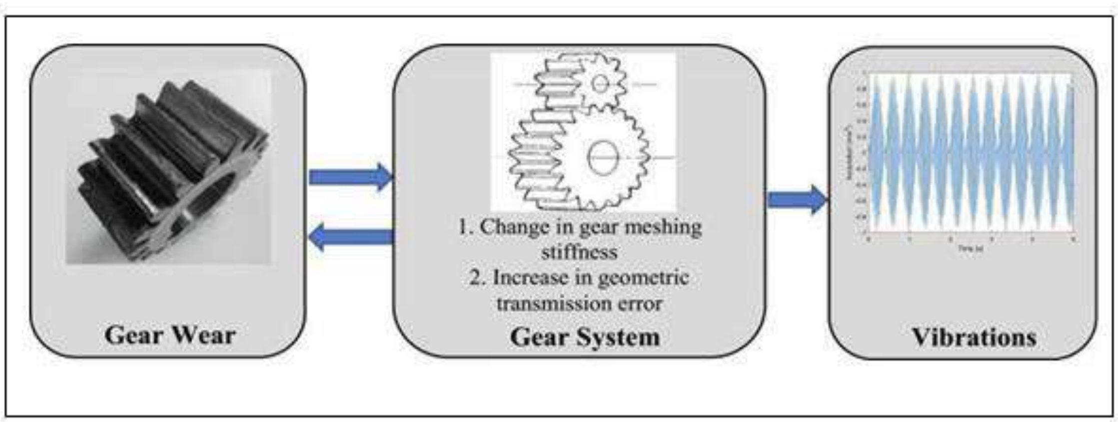

Figure 2: The interaction between gear wear and gear dynamics, and its induced vibrations

4. VIBRATION FEATURE BASED GEAR WEAR MONITORING

Changes in the tooth working surface due to gear wear also result in changes to the vibration characteristics of the gear. Some vibration characteristics will diverge more from their initial values as wear increases.

The impact of wear on gear performance can be assessed using these variances. Gear wear evolution tracking is the main focus of the current wear monitoring work. Additionally, the majority of research projects track changes in the gear tooth profile. On the other hand, very few research are focused on micro-level wear monitoring, such tracking the spread of fatigue pitting or identifying variations in surface roughness. There are fewer vibration-based methods for identifying the wear mechanism in gears than there are wear evolution tracking methods.

Abrasive wear, also known as extremely severe fatigue pitting, may cause a change in the gear tooth profile, or macro-level wear, which would raise the vibration signal's total energy and the gear meshing harmonics' magnitude. Investigating the connection between the degree of gear wear and the energy of the signal or the gear using mesh harmonics is therefore worthwhile.

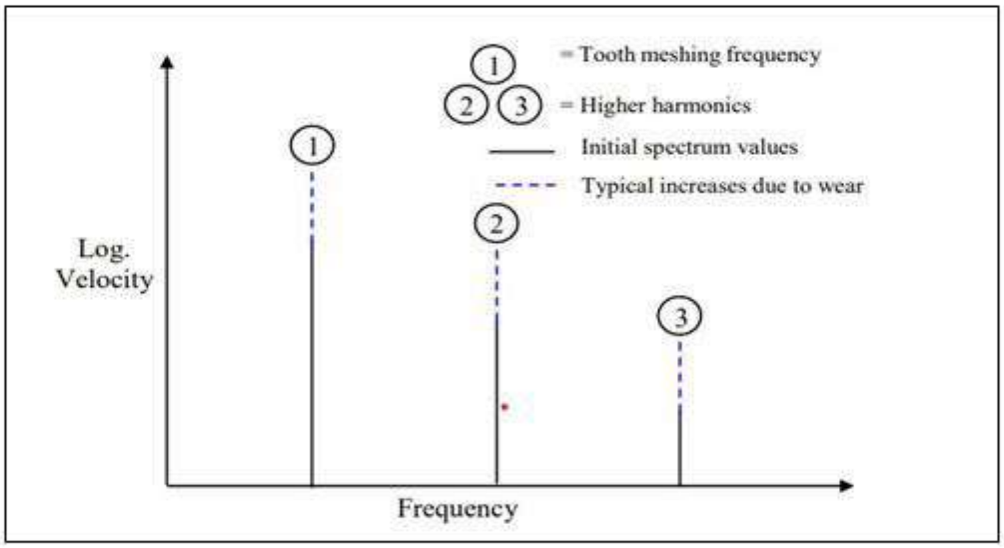

Figure 3: Typical vibration spectrum due to wear.

5. MODEL BASED GEAR WEAR MONITORING TECHNIQUES

Gear wear simulation is a powerful tool for tracking and forecasting gear wear. The main instruments utilised in the gear wear simulation to generate dynamic models and their interactions with one another are tribological (wear) models, gear meshing processes, and vibrations characteristics.

The established models therefore enable assessment and simulation of dynamic reaction (e.g., vibrations and contact force) in a variety of health settings, and they also enable the revelation and conclusion of the gear system's problem symptoms for failures diagnostics and prognostics

In the gear wear simulation, the connection among dynamic attributes (stiffness, friction, gearbox error, etc.) and system responses (dynamic forces and vibrational signals) is addressed by the gear dynamic models. Tribological models analyse wear rate, oil film thickness, and pressure distribution based on a range of inputs such as surface roughness, lubricant viscosity, load, and sliding velocity.

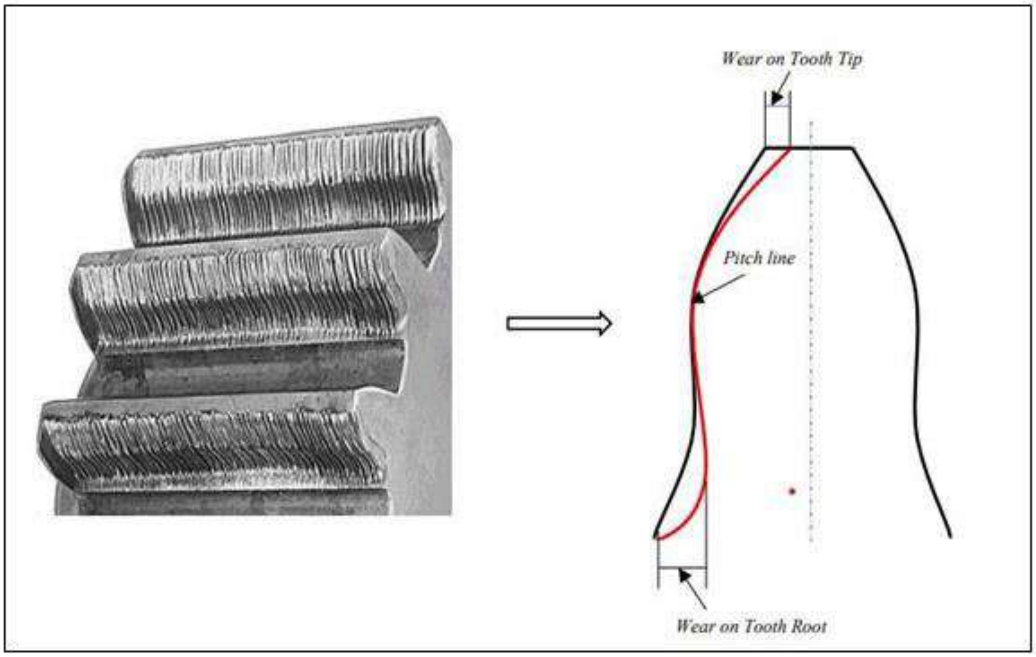

Figure 4: Wear distribution (abrasive wear)

They accomplish this by building a damage propagation model utilizing wear mechanism theories or experimental information. The subsequent sections will cover the research findings on the development of the gear defect model. Lumped parameter modelling (LPM) and finite element modelling (FEM) are commonly used to simulate the gearbox. When using lumped parameters model methods, the masses build up at specific locations and the modelling elements are rigid.

In contrast, a physical representation is discretized into separate, basic geometry-based components known as finite elements in finite element modelling techniques. The system response is then generated by joining or assembling all of the elements. Since every modelling strategy has unique benefits, it is challenging to definitively state which approach is better. [5]

The solution costs of these two different methods vary depending on the discretization properties of the LPM and different FEM derivations as well as the efficiency of the programmer. As was previously mentioned, if the boundary conditions and corresponding degree of discretization are well defined, then the two methods may be equally accurate.

This part will introduce the current gear wear monitoring approaches along with the application of LPM, FEM, and their combinations to produce a dependable and effective wear analysis. Since gear wear monitoring is the main topic of this review study, advancements in gearbox dynamic modelling techniques won't be covered in detail.

Rather, a few important dynamic model parameters that are closely linked to the gear wear progression will be presented and examined below. Therefore, in order to better understand gear fatigue pitting's propagation behaviours, more emphasis should be placed on creating it.

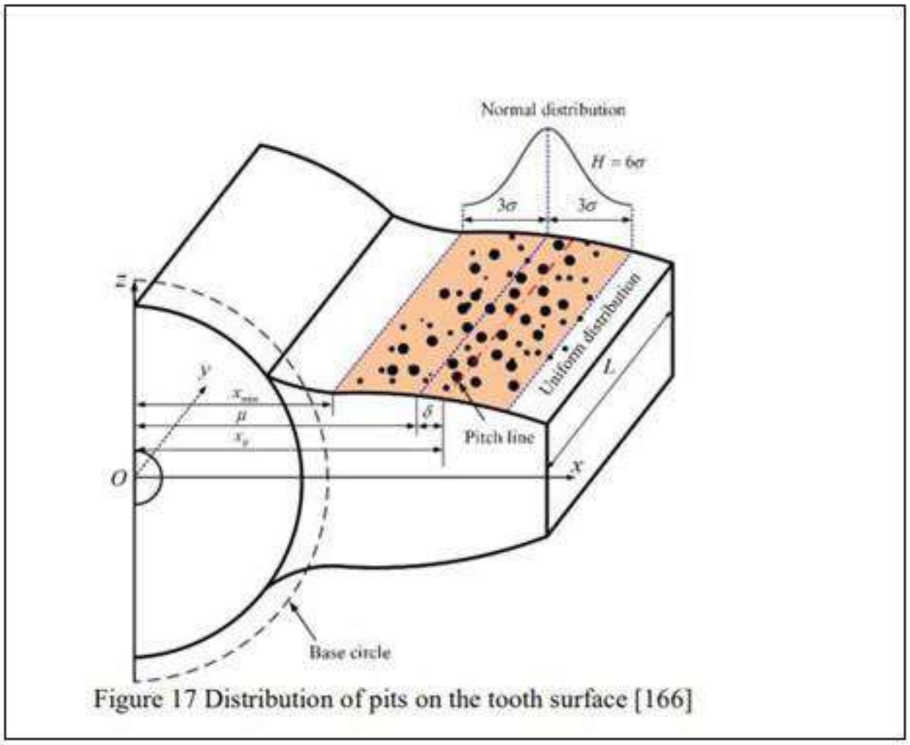

Figure 5: Distribution of pits on the tooth surface.

Moreover, studies examining the interaction between tribological and dynamical models for quantifying gear wear processes are still needed, considering a comprehensive dynamic model in addition to sufficient parameter (stiffness and GTE) assessment and model validation.

For wear analysis, it is therefore necessary to create a complete dynamic model with accurate meshing stiffness and GTE and validate it with real measurements to mimic realistic wear-induced vibration (in contrast to the actual running rig). [6]

6. GEAR DEFECT PREDICTION TECHNIQUES

Many industries would benefit immensely in being able to predict gear wear in terms of cost and safety. The current study involving vibrational gear defect prediction methods, using the Archrad wear model, will be studied and addressed in the sections listed below:

The gear system is often greased rather than dry, and effective lubrication can reduce noise and vibration, reduce permanent energy loss, and reduce tooth wear. As a result, the EHL model was used to simulate wear propagation behaviours and estimate cumulative wear depth given lubrication conditions. Due to time constraints and expert guidance, a new simpler EHL model was developed, which may also be specified using isothermal findings.

A finite element based gear model has been established in various research to estimate gear wear propagation for its accuracy, but its inability to accommodate dynamic system characteristics was its fundamental limitation. Gear wear monitoring along with prediction in industrial sectors urgently require a vibration-based device that can reveal gear wear and dynamic behaviour while also requiring just a minimum amount of experimental data for model equation updating/calibration. In addition to physical model-based gear wear prediction, many ways have been developed for tracking and predicting wear- induced tooth profile changes. [10]

In analyzing the advancement of vibration model-based gear wear monitoring, it was found that the Archard wear equation continues to play an essential role in modelling abrasive wear behaviours. The analytical frameworks for fatigue pitting are constrained, with the EHL model and fatigue criterion being the primary approach to investigate propagation behavioural patterns. However, establishing the model is time-consuming and requires expert knowledge. To better understand fatigue pitting propagation, more efficient and effective models/tools for replicating its behaviors would be greatly appreciated. [11-12]

In real terms, factors such as lubricant contamination, roughness variations, changing operating circumstances, and so on will influence the rate by which fatigue pitting and abrasive wear develops. As a result, in the absence of continuous monitoring and updating, forecast findings' accuracy is uncertain and may reduce substantially as wear occurs. To predict the pattern of gear wear propagation while taking actual measurements into consideration, reliable, effective, and cost-efficient vibration instruments are necessary. [11-13]

7. WEAR PREDICTION TECHNIQUES USING AI

The most popular methods for assessing tool wear are artificial neural networks and their variations. Modifications of ANNs are being applied and modified in a number of articles to improve wear monitoring performance under various cutting situations. A few studies attempted to increase the wear assessment algorithms' accuracy by utilizing a variety of sensors. But it did not ensure that the estimates would be improved. [13]

Numerous uncontrollable elements affect how long a cutting tool lasts. High speeds cause the tool-work piece contact surface to produce a significant amount of heat, which modifies the cutting edges through intricate physicochemical processes. The duration required to attain the upper bound of the wear test under particular cutting circumstances defines the tool life. [14]

To achieve the current results, a number of networks have been developed and evaluated in an effort to determine the ideal architecture, suitable activation function, and training methodology. The optimal performance of the network for four distinct variables was identified based on all neural network models that have been created (for diagnostic measurements depending on vibration and cutting strength signals). The practical disadvantage of this technique is that it necessitates the acquisition of two physical quantities: forces and vibration. Systems that rely on measuring several physical factors are often complex and expensive to implement. Therefore, in some cases, using straightforward measurement techniques (such as vibrations) is a better trade-off for more efficacy in determining the cutting tool's state. There are certain boundaries for compromise, but these ought to be examined in real-world situations. [14-16]

7.1 Vibration Signature Processing Techniques

One can identify and forecast the fault conditions in a gear box using a variety of vibration signature processing methods. Given the difficulty of evaluating the defect, a combination of genetic algorithms, artificial neural networks, and modified signal processing techniques can be used to streamline the method of detection. Listed below are a few methods of signal processing:

a. Time Waveform Analysis,

b. Analysis of Amplitude Modulations,

c. Spectrum Analysis,

d. Time Synchronous Averaging Analysis,

e. Frequency Spectrum Analysis,

f. Wavelet Analysis.

The accelerometer and FFT analyzer typically record vibration data in the time domain. In addition to gear failures, bearing failures and many other rotary component failures can also be predicted using the time domain data that was gathered. "Condition Indicators" (CI) are another name for these statistical characteristics.

One of the best ways to find and choose the ideal statistical feature for predicting faults using ANN is to use a genetic algorithm. The "Survival of the Fittest" theory underpins the operation of genetic algorithms (GAs). To find the best statistical feature (also known as a Condition Indicator, or CI) and arrive at the best possible solution, GA will carry out the necessary mathematical calculations. Furthermore, the Artificial Neural Network receives this chosen optimal feature as input.

An artificial neural network (ANN) is designed to determine the combined impact of a defective gear and bearing. ANNs are composed of multiple layers, including input, hidden, and output layers. Another name for this is a multilayer perceptron. The hidden layer in this multiple-layer structure could be made up of one, two, or more layers by itself.

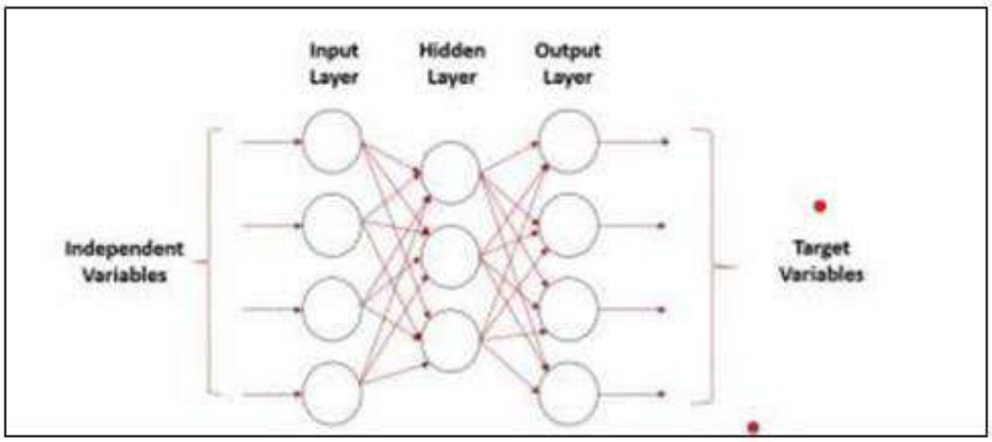

Figure 6: Artificial Neural Network Model.

The best feature retrieved from the Genetic Algorithm (GA) is what the independent variables are, and they serve as the ANN's inputs. The nodes are represented by the circles. Every node is linked to the nodes that came before it. The predicted outputs from the ANN are the target variables. The actual values are contrasted with those predicted outputs. Iterations are carried out till the difference between real and predicted value will be minimal by varying the weights in the layer that is hidden, so as to create a good ANN model. The ANN model can then be used to predict other models after obtaining the efficient difference.

When artificial neural networks (ANN) are properly implemented, it is possible to classify the presence of various fault conditions, such as combined gear and bearing fault detection.

8. CONCLUSION

An essential part of gearbox condition monitoring is gear wear monitoring. Vibration analysis is an ideal fit for gear wear monitoring since tooth wear significantly affects gear dynamics. A brief summary of the many modern vibration-based techniques for geared gearbox system condition monitoring is given in this study. A gearbox will frequently produce loud, periodic vibration signals. The majority of current studies have concentrated on monitoring the change in tooth profile brought on by abrasive wear, typically at the millimeter level (macro-level wear).

However, because fatigue pitting causes mild vibrations that are easily buried and covered up by background noise, wear mechanism identification and fatigue pitting monitoring—often at the micro- level—have gotten less attention. Apart from the physical model-based methods previously described, further methods have been established for fatigue pitting predictions. An artificial neural network (ANN) was utilized, for instance, to forecast the degree of gear fatigue pitting. The design standard of the American Gear Manufacturing Association (AGMA) was utilized to forecast fatigue fracture initiation and fatigue pitting resulting from bending behaviors along the gear tooth profile.

In industrial settings, fatigue pitting and abrasive wear can happen simultaneously or separately on the same gear during the gear surface degradation phase. Therefore, it would be ideal if it were possible to observe and predict the surface pitting density as well as the change in the gear tooth profile at the same time. In order to achieve this, it is necessary to quantify the wear-induced tooth profile change or alteration (in terms of wear depth) and surface pitting the density in situations where these two wear events happen either simultaneously or independently.

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