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Research Article

MONITORING CRACK PROPAGATION, IN A CYLINDRICAL GEAR TOOTH, USING VIBRATION SIGNAL

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ABSTRACT

The mechanical component that most fails in gearboxes are the gears. These failures usually occur before the end of useful life projected by criteria of failure standards, due to teeth defects as severe wear and cracking. The condition monitoring of gearboxes evaluates parameters which can indicate the mechanism of failure in process in the gear. The most commonly used monitoring techniques of gearboxes are vibration analysis and lubricant analysis. The experimental analysis consists of the evaluation of an experimental workbench under two conditions: notched gear for crack simulation and; gear with variation of notch for simulation of a crack propagation. The workbench condition was evaluated using vibration signal treatment techniques such as Time Synchronous Averaging, Residual Signal, Demodulation, Statistical Moments, Crest Factor and Statistical Analysis using Beta Probability Density Function .The vibration techniques were adequate to identify the presence of an evolution of the notch. Statistical analysis using Beta PDF was useful to identify the degradation of a tooth as the notch size evolved. The paper's novelty lies in its experimental analysis of a gear with a notch, which simulates the presence of a fracture. It aims to determine whether the system progresses towards catastrophic failure over time (tooth breakage) and examines the system's behavior under different loads and speeds.

INTRODUCTION

In many industrial applications, a gearbox is a common power transmission device that increases torque or output speed. Because it is a critical component, catastrophic failure of a gearbox can result in significant production losses due to downtime and consequent damage to the mating equipment [1].

Many machine elements can fail, but the gears are the most common cause of unplanned stoppage The gears are dimensioned according to meticulous and well-established norms that consider the typical failure modes: bending failure, which occurs when applied stress exceeds the bending strength limit of the tooth, and surface fatigue failure, which occurs when cyclic contact between the surfaces promotes wear [2, 3].

From the standpoint of tooth bending, a well-thought-out design that uses the appropriate materials to resist the applied stress would result in the gear having a theoretically limitless life, only failing due to the process of surface fatigue. In practice, however, this is not the case. Many circumstances that are not predicted by continuum mechanics can contribute to the failure of a gear tooth at loads that are lower than the design. Some case studies include the existence of cracks and profile abnormalities. As a result, it is critical to understand the behavior of the gear pair during surface fatigue and bending failure circumstances [4-6].

Wear evolution is a natural process in gearing that will occur eventually, depending on numerous design factors such as the surface hardness of the gears, the type of lubrication utilized, the forces transmitted to the gear pair, and the lubricant condition, among many others. Cracks, on the other hand, can arise from residual stresses caused by a variety of manufacturing processes, including thermal and surface treatments, microstructural inclusions, and surface fatigue, and others. The quantitative analysis of fracture formation and propagation is quite difficult and depends on several parameters. Even with such complexity, it is critical to foresee failures involving this process, especially regarding the overall manufacturing sector [7-9].

Equipment maintenance has changed over time as a result of the implementation of numerous concepts and techniques of intervention, such as corrective, preventive, and predictive maintenance. The ability to execute a prognosis of the machinery, i.e., to predict the useful equipment life based on a diagnosis of the same, has been the emphasis. However, to make an accurate prediction of the equipment's future condition, the techniques for detecting and analyzing the

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severity of malfunctions must be exceedingly accurate [10-12]. Among the different procedures for monitoring the state of the system, the most common and efficient, without interrupting production, are vibration monitoring analysis. It seeks to determine the condition of the equipment based on vibration signals produced by the various dynamic forces acting on the system [13, 14].

The current research aims to experimentally analyze a diagnosis of a gear with a notch, simulating the existence of a fracture, and determining whether the system evolved to a catastrophic failure over time (tooth breakage). Finally, the system's behavior is examined when it is subjected to a steady notch expansion. For that purpose, a thorough review of diagnostic techniques centered on vibration analysis was conducted to determine the most efficient methods for detecting the condition of the geared pair. The experimental stage of the project comprised the construction of a workbench constituted of a gearbox and a rotation multiplier gearing set. A frequency-controlled electric motor drives the apparatus. An electric generator is connected to the multiplier's driveshaft, and it, along with a panel of lamps, is responsible for supplying a resistive load to the system's rotation. The lubricant specified for the operating conditions of the apparatus was used to lubricate the system. The goal was for the lubrication to be a neutral factor, with the presence of particles in the oil caused only by the wear processes in the experiments.

The first experiment placed a notch in the root of a gear tooth with the purpose of favoring the propagation of a fracture from the notch due to residual mechanical stress and area reduction. The system's loading conditions and gear design were conducted out to favor the bending and surface fatigue failure modes, which, when combined, would accelerate the wear process and perhaps cause crack propagation. Whenever a vibration signal and an oil sample were taken, a visual check was performed.

The second experiment had the same conditions as the first one. The notch was gradually increased, and a vibration signal was acquired for each increment to analyze the defect's progression. Visual analysis was used to calculate the size of the notch based on relative positions. The best combinations of methodologies were sought in all proposed evaluations in order to establish the most efficient method of evaluation.
Several works dealing with damages in meshed systems have been done. In our work, the difference is the inclusion of a notch in a gear tooth, simulating a crack, with subsequent use of statistical analysis via PDF beta to identify the evolution of the notch size. The choice of using a notch, instead of a pre-existing crack, is due to the fact that we have better monitoring of crack propagation.

BIBLIOGRAPHY REVIEW

Silva [15] investigated the possibilities of vibration signal processing approaches in the monitoring of power-varying speed reducers. Time Synchronous Averaging (TSA), residual signal, temporal demodulation, variance, Root Mean Square (RMS), skewness, kurtosis, crest factor, spectrum, Short-Time Fourier Transform (STFT), Wavelet Transform, Wigner-Ville Distribution, and Weighted-Wigner-Ville Distribution were the techniques evaluated. He determined, using a signal simulator, that all techniques are subject to power variation and thus inappropriate for solving the problem. He also proposed three analytical methodologies based on the fourth statistical moment in relation to the origin of the Beta PDF (Beta Probability Density Function): (i) Overall Historical Analysis (OHA); (ii) Individual Historical Analysis (IHA); and (iii) Individual Independent Analysis (IIA). He tested all three approaches using singular torque or speed adjustments and two fault conditions: (a) no failure and (b) a damaged tooth. He experimentally demonstrated that all three procedures significantly suggest the existence of a broken tooth, and that both the IHA and the IIA can precisely identify which tooth is broken. Silva [16] assessed the behavior of the IIA approach employing Beta PDF, for fault identification of geared pairs with faulty assembly, specifically eccentricity and misalignment. The approach recognized the presence and progression of assembly faults but was unable to distinguish between them. It also demonstrated the technique's capacity to find the problem as the system speed increased.

Almeida [17] conducted an investigation into the relationship between vibration and lubrication of rotating machinery, examining the effect of lubricant viscosity variation on the vibration signal of gearboxes. The author was able to identify a characteristic of the vibration signal that may detect variations in the viscosity of the lubricating oil. Ebersbach [18] conducted research on the creation of an analytical technique for combining vibration analysis data with lubricant analysis data in equipment condition monitoring. For this, he conducted extensive literature research on the capabilities of monitoring approaches to discover various types of failures in a connected manner, with the goal of developing an artificial intelligence-based implementation. Finally, he created software capable of diagnosing equipment status based on data from lubricant analysis and vibration analysis.

METHODOLOGIES

The experimental part of this work focused on evaluating the wear behavior of a gear pair using two approaches: under the presence of a notch (simulating a crack), and evaluating the variation of this notch. The evaluation of this behavior was done using condition monitoring techniques, employing vibration analysis techniques.

An experimental workbench was settled up for this purpose at IPBEN- Institute of Bioenergy Research whose instruments used to get the vibration data belong to the Vibration Laboratory and the instruments used for oil sampling and sample analysis belong to the Tribology Laboratory. Next, it will discuss the assembly of the workbench and all its instrumentation, the experiments performed and the analysis techniques applied.

Experimental workbench

Silva [16] employed a similar experimental workbench model. A WEG CFW-08 frequency inverter controls the rotation of a WEG 100L FZ63836 electric motor, which drives a Cestari HS0 10L speed multiplier. To provide a resistive load to the system, a Kolhbach electric generator is connected to the multiplier's output shaft. The intensity of the load is adjusted by a panel of 4 kW lamps connected to the electric generator. The entire set was mounted on bases that were mounted on a robust metallic table with wheels for vibration attenuation.

Figure 1 illustrates a schematic depiction of the experimental workbench.

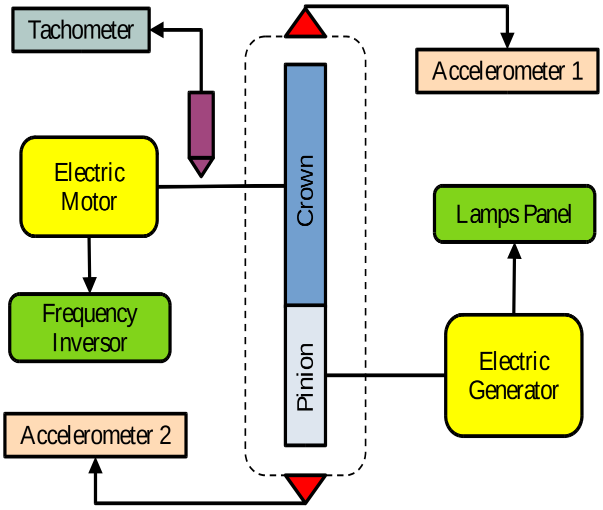

Fig 1 Schematic depiction of the experimental workbench.

The electric motor has a power rating of 3.7 kW and a nominal rotation speed of 1715 RPM, while the geared pair multiplies the rotation of the input shaft by 2.16 (the crown has 95 teeth and the pinion has 44) and can reach a maximum rotation speed of 3700 RPM. The electric generator, with a nominal rotation of 1800 RPM and a power of 4 kVA, imposes a resistive load and operates as the system's rotation controller. As a result, the spinning of the electric motor is limited to 834 RPM, reducing its usable output. Figure 2 presents the system's operational torques and powers, as well as other operating characteristics.

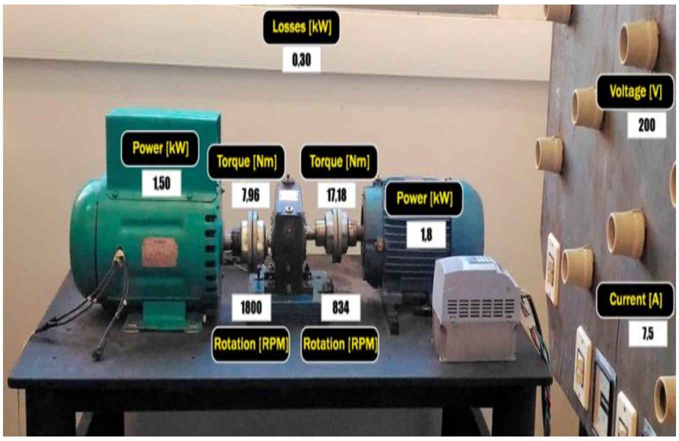

Fig 2 Operational parameters of each component of the experimental workbench.

Table 1 Dimension parameters and failure criteria of the geared pair.

Parameter	Pinion	Crown
Nominal diameter	44 mm	95 mm
Teeth number	44	95
Face width	10 mm	10 mm
Superficial hardness	230 HB	230 HB
Bending factor	0.925	1.0063
Wear factor	1.497	2.2961

Source: Elaborated by the authors.

Initialization and operation procedures

To provide reproducibility for the experiment, a consistent approach was established to initiate the operation of the experimental workbench. The adopted routine involves manually checking the tightening torques of all fastening elements, including the component bases and the speed multiplier cover, to ensure that mechanical clearances were minimal and constant throughout the experiment; the lubricating oil level was checked to avoid leaks; the system was started at low rotation and without resistive load; the rotation speed was gradually increased and, at each increase, a lamp column was activated. In this step, the voltage value was evaluated: values higher than 220 V implied that the rotation generated enough voltage to turn on the next column (also avoiding damage to the lamps, suitable for this voltage); when the desired load was reached, the rotation frequency of the electric generator was checked and, if necessary, adjusted to the nominal rotation, waiting about 30 minutes until the whole system stabilized, reaching a final operating temperature. Several inspections were routinely monitored during the system's operation to ensure the consistency of the operation parameters, including: checking the temperatures of critical operation points with an infrared thermographic camera; checking excessive vibrations with accelerometers and signal conditioners; checking the condition of the lamps with an inspection of amperage, voltage, and frequency on the lamp panel; and inspecting the workbench to identify leaks. Before shutting down the system for oil collection and analysis, the operating parameters were checked and, if any were incorrect, a correction was made and time was granted for the system to stabilize again; for safety reasons, the workbench was also gradually reduced until it was completely stopped. The methods utilized to collect the vibration data will be covered in a separate topic. Finally, for online monitoring of the bench operation, a camera surveillance system was installed.

Experiments

Some elements were kept constant during the experiments to promote repeatability and control in the collection of experimental data: the lubricating oil Texaco Gear Oil SAE 90 used in the gearbox is the one suggested by the manufacturer. It was refilled with hygiene and care each time an oil sample was taken for analysis; in all experiments, the load on the output shaft and the rotation of the shafts were kept constant, and the monitoring was done with the help of the lamp panel; and finally, the experiments were performed in a laboratory environment with a controlled temperature. Two experiments were carried out in this investigation, which are outlined below:

Experiment 1 – The first phase involved putting a notch in one of the gears' teeth to simulate the existence of a crack. Figures 3 and 4 display the notch machining process using wire Electrical Discharge Machining (EDM) and the notch dimensions, respectively. Initially, it was observed if the monitoring instruments were capable of diagnosing the failure, and then it was determined whether such a condition would imply failure evolution. The conditions were examined every hour for a period of 12 hours to see if a catastrophic collapse would occur, which was not desired at this time. If failure did not occur, the maximum time of the experiment was changed to 360 hours in order to have enough data for analysis while avoiding the strong propagation of wear, which could alter the data.

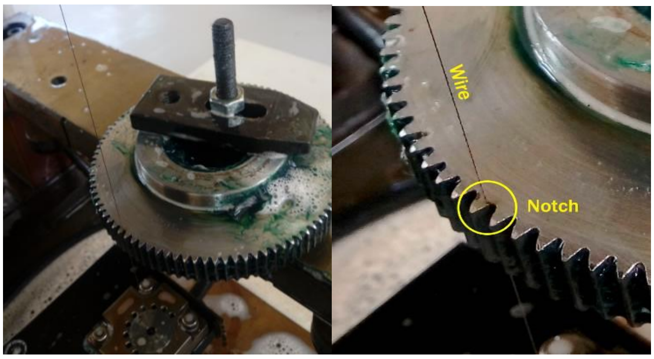

Fig 3 Process of machining a notch in a gear tooth using wire EDM.

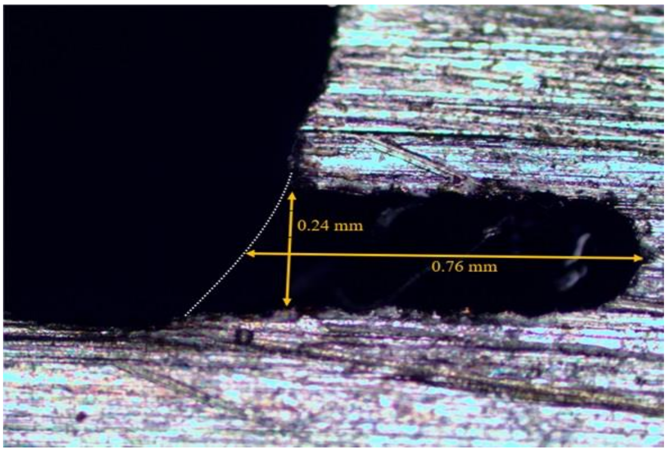

Fig 4 Notch dimensions along the gear tooth face.

Experiment 2 – The second phase involves gradually removing material from the base of one crown tooth and evaluating the behavior of the vibration signals for each circumstance, with the goal of identifying the pattern of parameter evolution from the vibration techniques. The notch machining process used the wire EDM process again performing a steady growth of the notch. Figure 5 illustrate the Notch increase.

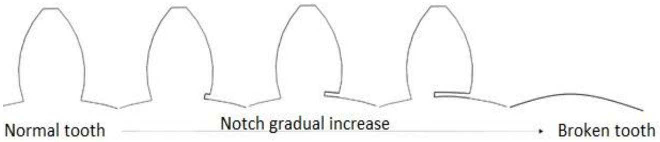

Fig 5 Notch gradual increase for the experiment

Instrumentation and data extraction procedures

Some tools were employed to acquire the data. The description and function of the instruments are presented in the sequence based on the analysis performed.

Vibration data extraction

In order to study the geared pair, two MMF KS50 accelerometers (with sensitivity of 2.29 mV/ms^{-2} and resonance frequency of 5 kHz) were installed in the gearbox using magnetic bases, one near the crown and the other near the pinion, as shown in Figure 6. Only one of the accelerometer signals was used to assess the results, while the other was used to validate the data. In addition to the accelerometers, a tachometer was employed to control the rotation of the geared pair's input shaft. Tachometer is also essential to implement the Time Synchronous Averaging (TSA) technique. An adjustable base was used to secure the tachometer.

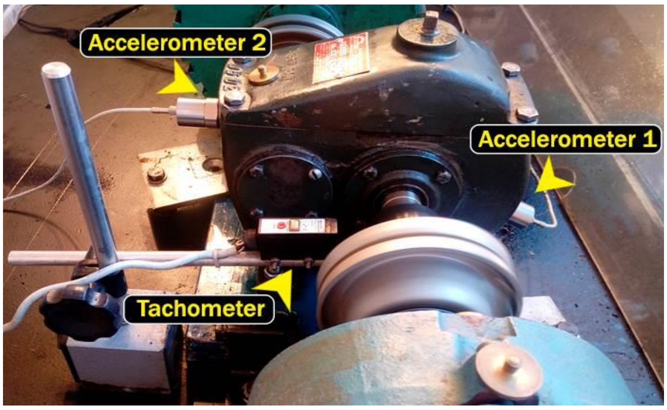

Fig 6 Position of the accelerometer and tachometer in the experiments

The vibration signal data gathering system begins with the aforementioned accelerometers and continues through two Robotron Schwingungsmesser 00042 signal conditioners, a Superlogics 32 16-channel PCM 32 analog-to-digital conversion board, and a Toshiba Satellite 2180 CDT notebook (AMD K6 processor and 64 Mb of RAM) with IOTech and DasyLab v4 signal acquisition software. Before beginning the experiments, the entire measurement equipment was calibrated. The vibration signal was sampled in the DasyLab program according to the flowchart in Figure 7. The application gathered data from two accelerometers and a tachometer. Table 2 describes the functions of each flowchart element.

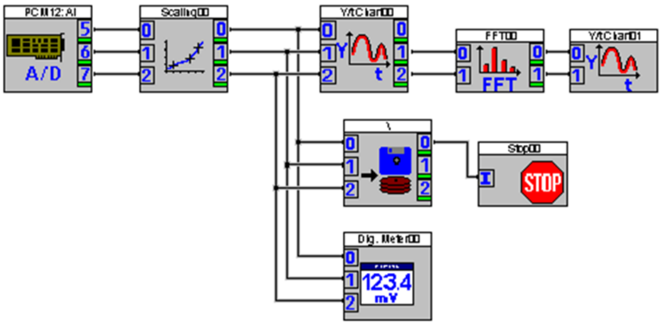

Fig 7 Flowchart of signal sampling steps in the DasyLab software.

Table 2 Function of the program elements in the DasyLab software

Element	Function
PCM 12: AI	Represents the signal acquisition by the acquisition board
Scalling00	Represents the scaling gain process of the signal
Y/t Chart00	Plots the signal amplitude over real time
FFT00	Applies the Fourier Transform to the signal
Y/t Chart01	Plots signal amplitude over frequency in real time
Save	Records vibration signal data
Stop00	Ends one sampling step and starts another until the total number of blocks
Dig.Meter00	Provides measurement amplitudes in Volts in real time

Source: Elaborated by the authors.

The sampling frequency was set to 10000 Hz, with 4096 points per block and 300 blocks totaling 1228800 points.

Techniques and performed analyses

The DasyLab software generates an ASC file containing the vibration data. A pre-processing was carried out in order to remove extraneous information for the examination of the results. Following that, a set of computational algorithms was created using the MATLAB software. The flowchart for the procedures is shown in Figure 8.

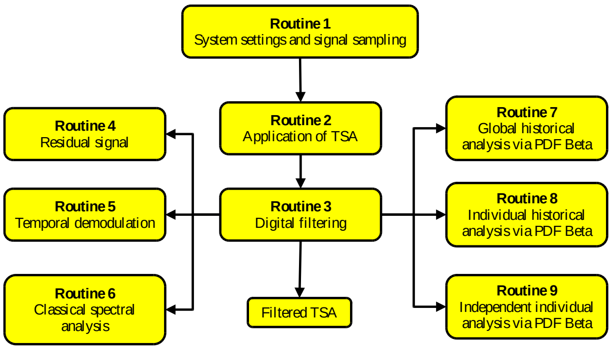

Fig 8: Flowcharts of vibration signal analysis routines**.**

Routine 1, titled "System settings and signal sampling", is responsible for configuring the system and signal sampling parameters. It is also defined the number of turns used to apply the TSA for a more realistic individual analysis of each gear, taking into account that the geared teeth at the start of the experiment take a certain number of turns to match again, so a minimum number of turns was defined to ensure that all the teeth suffered gearing at least once between them.

Routine 2, "Application of TSA", is responsible for normalizing the tachometer signal. In practice, this type of signal has amplitude changes, and in order to identify the points that determine the period of a gear, a square signal with a maximum and a null value is required, which is only feasible after normalizing. With the period calculated, the rotational frequencies of the gears, as well as the Gear Mesh Frequency (GMF) and its harmonics, may be identified.

Routine 3, called "Digital filtering", is a routine in which digital filters are used, as follows: high-pass filter with cutoff frequency of 1000 Hz; low-pass filter with cutoff frequency of 300 Hz; band-pass filter in the range 300 to 1000 Hz; band-pass filter of plus and minus 300 Hz around GMF, the 1st harmonic of GMF and the 2nd harmonic of GMF; and band-pass filter of plus and minus 100 Hz around the two supposed resonant frequencies of the system. In the filtering around the GMF is obtained the signal that will be used in the analysis of the TSA itself and in routines 4 to 9.

Routine 4, called "Residual signal", applies a band-reject filter to the filtered TSA signal at plus and minus 70% of the frequency of the lowest rotation found in the GMF gear frequency and all its harmonics, leaving only the sidebands of these frequencies.

Routine 5, called "Temporal demodulation", applies the Hilbert Transform (HT) around the GMF to find the greatest distance from the center to the orbit on the Cartesian chart between real and imaginary values.

Routine 6, called "Classical spectral analysis", applies the Fast Fourier Transform (FFT), transforming the signal from the time domain to the frequency domain.

Routine 7, called "Global historical analysis via Beta PDF," normalizes the filtered TSA signal around the GMF and calculates the beta distribution of the signal and its parameters.

Routine 8, called "Individual historical analysis via Beta PDF ", performs the same procedure as Routine 7. In the sequence, the signal is divided into a number of equal points where each block represents the gearing of a single tooth, since the entire TSA signal represents one complete turn. For each block of points, the beta distribution and its parameters are obtained. The beta distribution and individual parameters of each tooth are then compared to the beta distribution and parameters of a complete reference signal (representative of a healthy gear condition).

Routine 9, called "Independent individual analysis via Beta PDF", performs the same methodology presented by Routine 8, but after obtaining the beta distribution and the individual parameters of each tooth, a comparison is made with the beta distribution and the parameters of the complete signal being analyzed.

Time Synchronous Averaging (TSA)

It is recommended that the TSA be conducted over an integer number of gear rotations while acquiring the vibration signals, because the combination of a given set of teeth will only repeat when the number of rotations of the pinion and crown is an integer [1].

Because the presence of GMF harmonics may represent additional problems such as misalignment and eccentricity, the general technique of the TSA calculation for the gearing analysis was done around the GMF. Because the purpose of the study is to discover point defect situations in all experiments, such as the existence of cracks or surface wear, the following calculation procedure was used:

1) Loading and adjusting the signals of each accelerometer and tachometer;
2) Adjusting the tachometer signal to correctly identify the number of turns of the crown and the starting points of the turn;
3) Separation of the accelerometer signals into a block of points according to one turn of the crown;
4) Calculation of the TSA;

5) Filtering the signal around the GMF, performed through a bandpass filter of plus and minus 300 Hz from the GMF;
6) Plotting the representative TSA signal of one lap over time.

Residual signal

A signal will have a peak amplitude at the GMF by definition. The differences in the sidebands, on the other hand, represent changes in the vibration pattern, which is the purpose of this work. In order to better assess these changes, the residual signal attempts to eliminate the GMF. The residual signal calculation technique consisted of the following steps:

1) Calculation of the TSA;
2) Application of a digital band-reject filter around the GMF and all its harmonics. The filter is plus and minus 70% of the lowest rotation frequency, so that no sidebands are eliminated from the signal;
3) Plotting the signal over time.

Temporal demodulation

Temporal demodulation is a signal treatment that aims to identify the behavior of the sidebands around the center frequency, in this case, the GMF. The Hilbert Transform (HT) transforms the signal into complex components, representing amplitude (real part) and phase (imaginary part) of the sidebands behavior, and plotting the real components by the imaginary ones gives us a parameter of the sidebands behavior. The procedure for calculating demodulation was:

1) Application of the bandpass filter around the frequency that is modulated to be analyzed, in this case, the GMF. A filter of plus and minus 300 Hz was set;
2) Application of the Hilbert Transform;
3) Plotting the Cartesian graph of the real component by the imaginary component;
4) Analysis of the amplitude through the maximum orbit distance; and, through a qualitative process, it is also possible to analyze the phase of the modulated signal, observing the behavior of the orbit on the graph.

Classical spectral analysis

The Fourier transform allows us to observe the behavior of the characteristic frequencies of a signal. The procedure for calculating the spectral analysis was:

1) Application of the Fourier transform using the Fast Fourier Transform (FFT) algorithm;
2) Correction of the FFT results, since the MATLAB function generates a double-sided spectrum and we wish to focus only on the one-sided spectrum in order to obtain the true amplitudes;
3) Plotting in the frequency domain.

Statistical analysis via Probability Density Function Beta

We use the beta distribution of the signal to diagnose the situation when studying vibration signals. To begin, we use the TSA signal filtered around the GMF to extract gearing information. The signal was normalized using the methods outlined in the works of SILVA [15] and is represented in Figure 9.

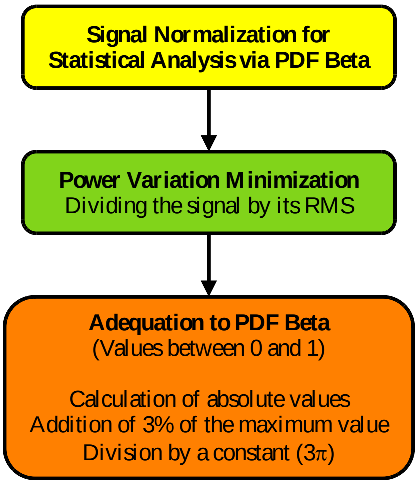

Fig 9 Schematic flowchart of normalization of the vibration signal for applying the beta distribution.

We used three statistical evaluation techniques: global historical analysis, in which the beta distribution (or some parameter thereof) is compared historically; individual historical analysis, in which a relative parameter called gear condition is created by comparing the representative subsamples of each gear tooth with a global sample representative of a good condition signal; and individual independent analysis, in which a relative parameter is also defined, where each gear tooth is compared to a global sample representative of a good condition signal. The fourth statistical moment with respect to the origin is the difference between the individual and global samples. Figure 10 illustrates a schematic depiction of the Beta PDF methodology.

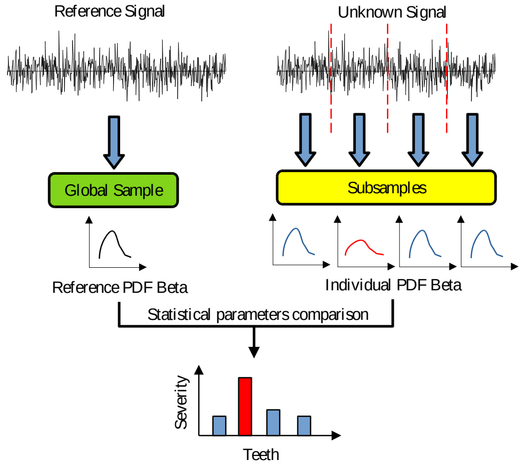

Fig 10 Schematic depiction of the Beta PDF methodology.

The reference signal for the individual historical analysis was defined after Experiment 1, which was the initial signal of the experiment. Another alternative would be to use the initial signal as soon as the system's transitory phase is over.

RESULTS AND DISCUSSIONS

This section will describe the condition monitoring data acquired in the two planned experiments.

Experiment 1 – Notch

The first experiment involved creating a notch in the root of a crown tooth to simulate the presence of a crack. As previously stated, the notch was created using a wire EDM procedure. The first phase of this experiment's analysis is to see if vibration signal analysis tools can detect the presence of the notch in the gear. The experimental workbench was then put through 360 hours of experimenting to see if the fault propagated (notch).

It should be emphasized that data was collected for 360 hours of experimenting of the geared pair running under healthy conditions, i.e., new (recently machined) and free of faults, for further comparative analysis.

As illustrated in Figure 11 (a), a vibration signal sample is acquired at the start of the experiment. The TSA is then applied, and the data is separated into blocks corresponding to one rotation of the crown, as shown in Figure 11 (b), before being filtered at plus and minus 300 Hz around the GMF, as shown in Figure 11 (c). By studying the filtered TSA, a band of gearing with noticeable peaks between teeth 70 and 76 can be identified. Finally, Figure 11 (d) shows the application of the residual signal, which exhibits very similar behavior to the filtered TSA, with peaks seen between gearing teeth 70 to 76.

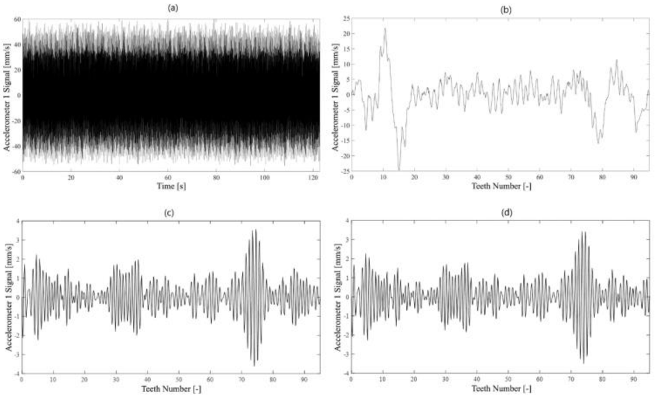

Fig 11 Accelerometer 1 signals collected and evaluated during Experiment 1.

Temporal demodulation

The presence of the notch was detected via temporal demodulation. This can be noticed by examining both the orbit's fluctuation and its maximum distance, as shown in Figure 12.

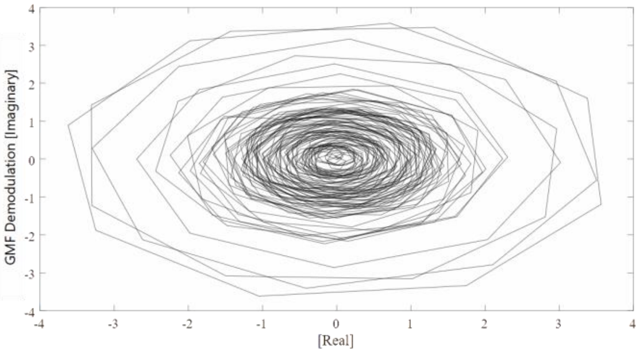

Fig 12 Accelerometer 1 signals collected and evaluated during Experiment 1.

Statistical Analysis via Beta Probability Density Function

The statistical analyses using the probability density function were also quite effective at detecting the presence of the notch. Figure 13 shows the Individual Historical Analysis (IHA), while Figure 14 shows the Individual Independent Analysis (IIA).

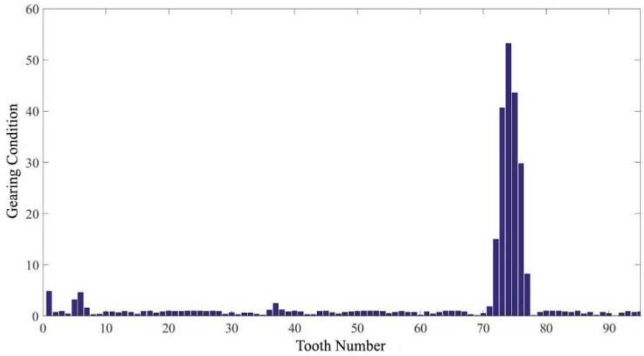

Fig 13 Individual Historical Analysis (IHA) for the first signal of Experiment 1.

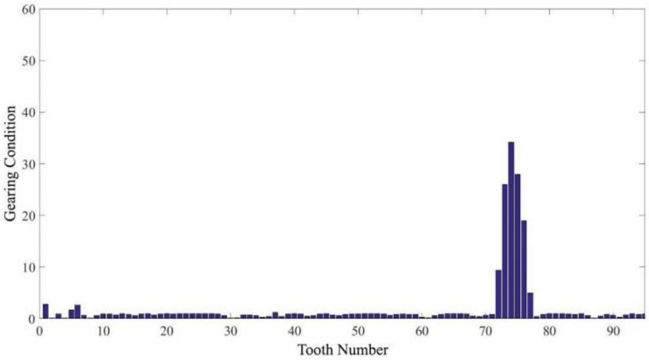

Fig 14 Individual Independent Analysis (IIA) for the first signal of Experiment 1.

The Historical Individual Analysis responds very well to the presence of the notch due to the use of a reference signal, in a healthy condition, mentioned above. Despite lower amplitudes, the Individual Independent Analysis is also able to detect the presence of the notch.

STATISTICAL PARAMETERS

To test the effect of the notch on the absolute values of the filtered TSA's statistical parameters, each parameter was compared during the 360 hours of the reference state (healthy) with the 360 hours of Experiment 1, as shown in the figures: mean (Figure 15), RMS (Figure 16), variance (Figure 17), shape factor (Figure 18), crest factor (Figure 19), skewness (Figure 20), and kurtosis (Figure 21).

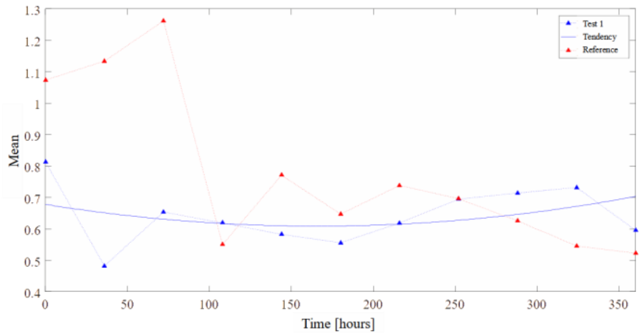

Fig 15 Mean parameter of filtered TSA of Experiment 1.

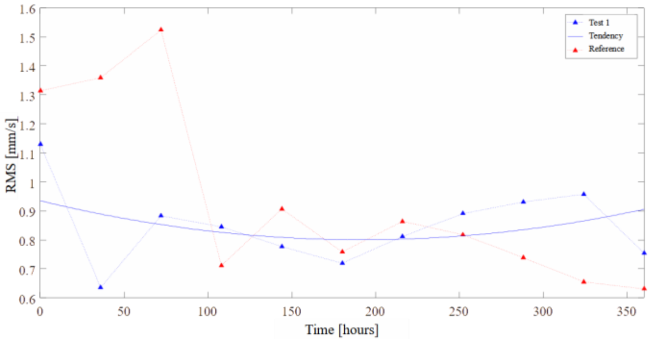

Fig 16 RMS parameter of filtered TSA of Experiment 1

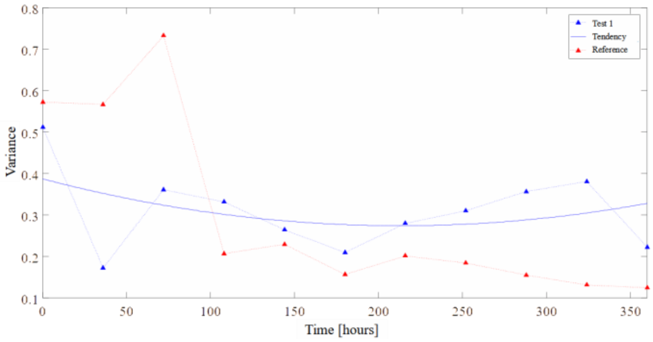

Fig 17 Variance parameter of filtered TSA of Experiment 1

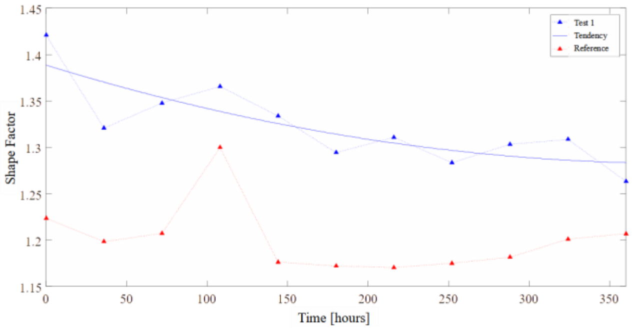

Fig 18 Shape Factor parameter of filtered TSA of Experiment 1.

The mean, RMS, and variance of the above-mentioned measures for notch detecting ability did not show the presence of the notch in the gear tooth. The shape and crest factors demonstrated the presence of the notch quite well, whereas skewness and kurtosis produced the greatest findings. In terms of evaluating the defect evolution, parameters such as the mean, RMS, and variance stayed nearly constant over time, while the others tended to decline. Because the notch was insufficient to produce the appearance and propagation of cracks, resulting in tooth breaking, the first three factors show little difference. Individual statistical evaluations using Beta PDF (Figures 22 and 23) and microscopic observation of the notch demonstrate that the notch size does not evolve (Figure 24).

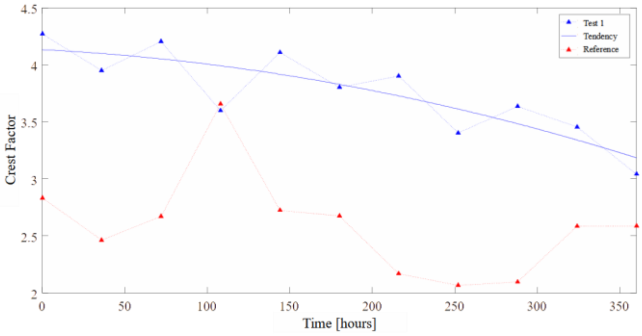

Fig 19 Crest Factor parameter of filtered TSA of Experiment 1

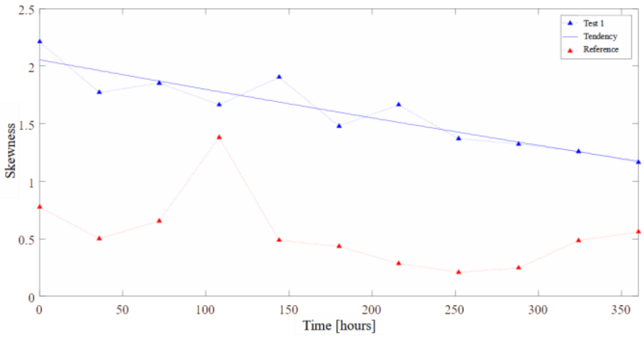

Fig 20 Skewness parameter of filtered TSA of Experiment 1

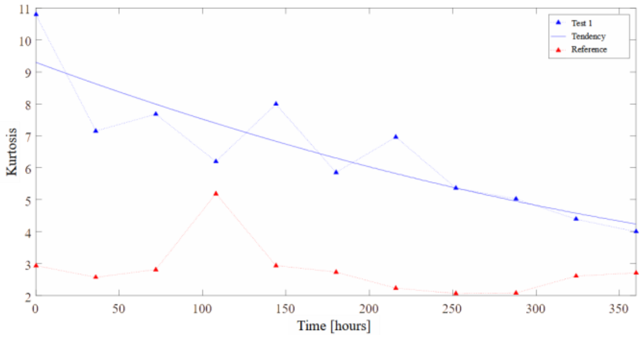

Fig 21 Kurtosis parameter of filtered TSA of Experiment 1

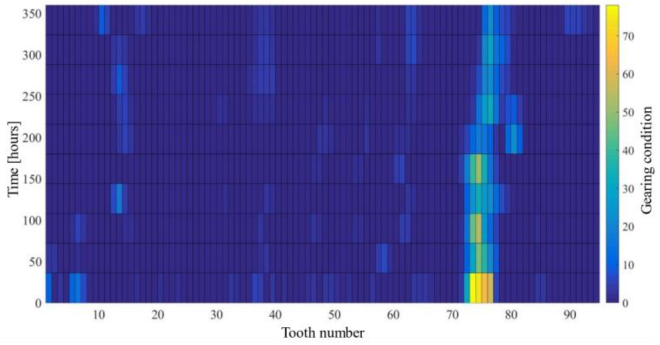

Fig 22 Individual Historical Analysis of Experiment 1

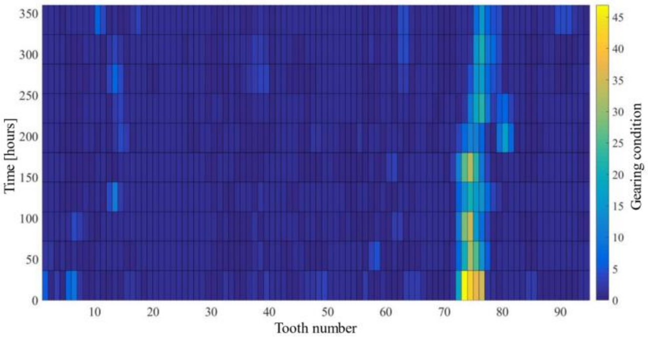

Fig 23 Individual Independent Analysis of Experiment 1

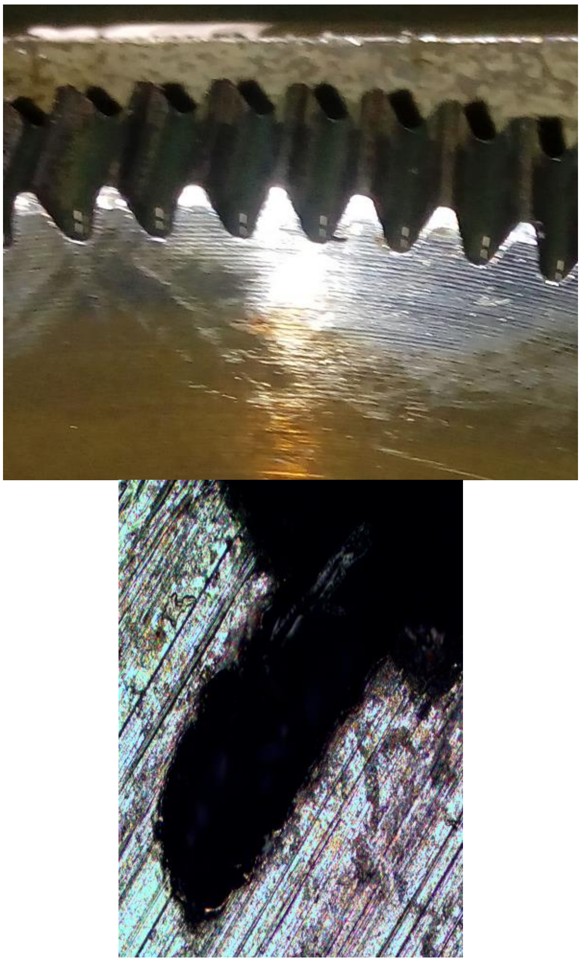

Fig 24 Microscopy analysis of tooth notch

Experiment 2 – Notch increasing

The second experiment involved gradually removing material from the base of a tooth in order to correlate vibration signal analysis techniques with the severity of the defect, which in this case was a notch. Figure 25 shows the evolution of the notch.

It was just performed statistical analysis via beta probability density function to assess the individual evolution of the region where the tested tooth was present because the test was performed on the same gear that had the notch produced by EDM. Other techniques might be influenced by the presence of the notch since the vibration pattern changes in the global signal when an abnormality is present. Figure 26 shows the Individual Historical Analysis and Figure 27 shows the Individual Independent Analysis both using the beta probability density function.

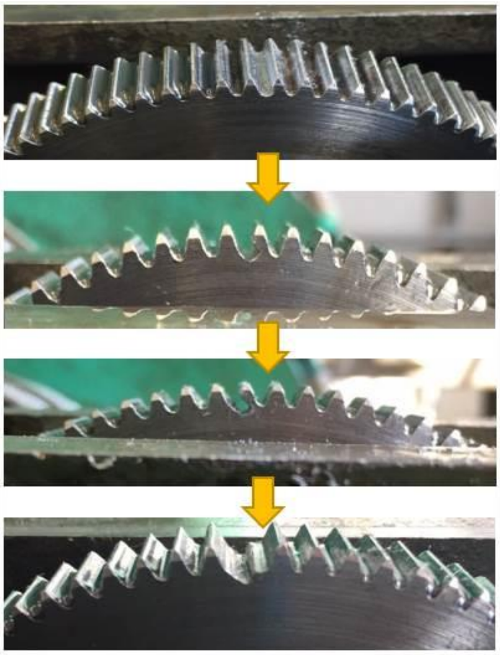

Fig 25 Notch expansion process in the crown tooth root.

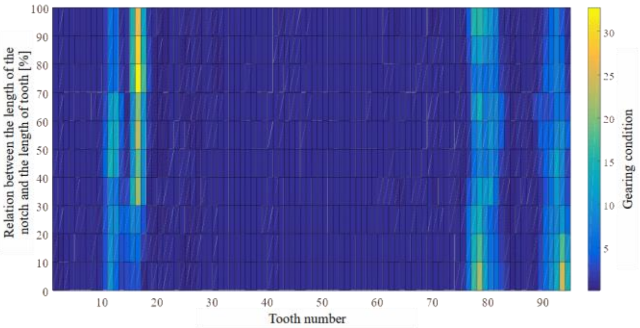

Fig 26 Individual Historical Analysis of Experiment 2

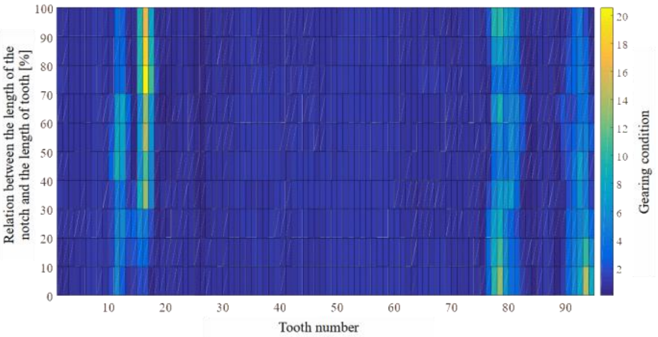

Fig 27 Individual Independent Analysis of Experiment 2

Individual analyses using PDF Beta can identify the evolution of the notch size, according to the gearing condition maps (as seen in tooth 16). Because it uses a signal in good health as a reference, the Individual Historical Analysis in Figure 26 is more appropriate. The abnormality was expected to be more noticeable between teeth 70 and 76. However, tooth 16 shows signs of progressive deterioration. It was discovered that there was most likely a change while using the tachometer, because slight adjustments from one signal to another shifted a tooth's location in the graph. One technique to reduce this effect is to adjust the signal sample such that each gear cycle includes more points. Another aspect that may have caused the change in results is the pinion, as it was discovered that several of its teeth were destroyed during the research, despite the fact that the TSA was designed to limit the effect of pinion impulses.

In Figure 28 we evaluate the evolution of the DMR4O parameter (Gearing Condition) as a function of the notch length to tooth size ratio using the individual historical and independent analyses.

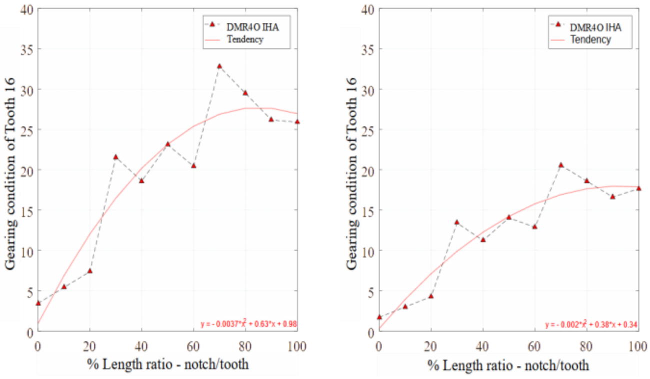

Fig 28 DMR4O in relation to notch size through Individual Historical Analysis and Individual Independent Analysis.

The behavior of the Gearing Condition of tooth 16 is consistent with the loss of tooth stiffness caused by the removal of material in the direction of the tooth root base line. Again, the Individual Historical Analysis is better able to detect the evolution of the defect.

CONCLUSIONS

Experiment 1 demonstrated that vibration analysis techniques may be used to detect the presence of a notch in gear teeth. The shape factor, crest factor, skewness, and kurtosis were the metrics best capable of spotting the notch. The presence of the notch was detected via TSA detection, residual signal, and especially temporal demodulation approaches. Finally, the color map of the classical spectral analysis and the individual analyses (IHA and IIA) were effective in locating and measuring the notch failure. The integration of all procedures opens up a wide range of possibilities for assessing structural condition.

Experiment 2 demonstrated that statistical analysis utilizing the beta probability density function detects the evolution of the notch length, establishing a baseline for future research into monitoring crack propagation in gear teeth using vibration signal patterns.

In a new works on vibration analysis of geared pairs, it is being used signal processing approaches in the time-frequency domain, such as short Fourier transform (STFT), wavelet transform, and Wigner-Ville distribution. It is advised that dynamic models be used to simulate crack propagation behavior, producing simulated signals, and using vibration analysis techniques to verify the occurrence. It is recommended to employ more exact material removal techniques to obtain the notch and a larger number of notch sizes for evaluation when studying the vibration response of a geared pair with a notched tooth. It's also a good idea to experiment with different notch shapes.

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Date availability

The data used to support the study can be available upon request to the corresponding author.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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