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A Review on Gearbox Condition Monitoring and Signal Analysis Techniques

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ABSTRACT

The manufacturing industry propels the globe forward. Every manufacturing business has many machines and gears for power conversion, speed reduction, and torque amplification, and many of them can be controlled. It is projected that 10 million new gearboxes enter service each year, with a total component value of more than $5 billion. The reliability of gear driven machinery and gearboxes is critical to industry's economic viability. Any malfunction in the machinery can lead to a significant breakdown expense. This paper includes a review of the literature on methods for signal analysis and gearbox condition monitoring. The approaches and components utilised in condition monitoring are covered in this paper. The vibration signal of a gearbox bears the characteristic of a gear failure, hence it can be used to detect gearbox breakdowns early on by evaluating the signal with various signal processing techniques. Gearbox vibration analysis is a simple, inexpensive, and dependable method of detecting problems early on and avoiding costly gearbox repairs and unnecessary shutdowns.

1. Introduction

Condition-based monitoring is a maintenance strategy that helps us make maintenance decisions based on the equipment's current state or health. Gathering all data and storing it on a computer is what data acquisition includes. After data has been acquired, it must be processed into graphs or charts. Vibration, temperature, pressure, strain, and noise are examples of measurements that convey information about the state of a machine or a physical setup or component. Vibration is the most widely used criterion to evaluate the state of gearbox components. Machines or machine equipment can be monitored using vibration measurement, acoustic emission technology, or an oil analysis approach. The metrics utilised to draw conclusions are acceleration and stress [1-3].

The statistical parameters from the measured signals are analyzed in cases of time investigation. The Fast Fourier Transform (FFT) of the measured signal is investigated in cases of frequency examination, and the wavelet analysis of the measured signal is carried out in cases of time-frequency examination methods. Wavelet analysis offers a more accurate and focused conclusion since it provides data on both a temporal and frequency scale.

Industries nowadays are working to cut costs and encourage competitiveness. A machine defect may cost more. Industries are paying a considerable amount of money towards upkeep of facility operations. According to the reports, up to one-third of the cost of production is spent on maintenance. Costs can be reduced by the provision of continuous and dependable functioning. Because of this, an efficient condition monitoring and maintenance system is required. To prevent downtime, a good condition observation system should be used in conjunction with maintenance procedures. This will boost productivity and be more cost-effective.

There are several important and dependable machines that are very important to the industrial process. These machines' failure may result in a shutdown, which raises the cost. Therefore, decreasing downtime and maintenance costs greatly depends on the early detection of the issue in those machines equipped with the productive condition watching system. Damage to one part of the machine has the potential to spread to other parts that are close by. This can be prevented by utilizing the condition observation system. The industries should integrate an observing system in machines for early detection of machine flaws so that preventative maintenance may be anticipated with the availability of the newest and most powerful software technologies, low-cost sensor technology, and smart instrumentation system.

Major challenges of gearbox condition monitoring are gear misalignment, gear wear, overload on tooth, gear eccentricity, excessive backlash, oil leakage, debris in oil and hunting tooth frequency, gearbox datasets, mechanical dataset, lubrication analysis and vibration analysis.

2. Literature review

Gearboxes are the primary source of vibration, according to Yuanyuan Huang et al. and engine ignition has a significant impact on engine-gearbox systems. One of the most important elements affecting the system's working performance is gear vibration. Gear vibration's most prominent characteristic signal is meshing frequency [4]. Therefore, in order to monitor the condition of an online mechanical system, it is necessary to ascertain the frequency of gear meshing. To extract gear characteristic signals, a variety of techniques have been developed, including spectrum kurtosis, empirical mode decomposition, intelligent deep learning, envelope demodulation, wavelet transform, etc. The tunable-Q wavelet transforms (TQWT) and The sparse breakdown of signals based on resonance (RSSD) approaches are the most often utilised methods for identifying gearbox features. The AR-ORSSD (Auto Regression – Yuanyuan Huang et al. used the Signal Sparse Decomposition technique (Optimised Resonance based) to ascertain the gearbox vibration signals. The RSSD approach distinguishes between the engine ignition and gear meshing impacts.

The gearbox vibration signals were identified by Yuanyuan Huang et al. using the Optimised Resonance based Signal Sparse Decomposition) technique. The engine ignition impact and the gear meshing impact can be distinguished from one another using the RSSD technique.

Gear meshing operations cause meshing impacts between meshing tooth pairs. As a result, the gear vibration signal contains both gear meshing impacts and ordinary gear meshing vibrations. The AR model, according to Yuanyuan Huang et al., is a statistical technique for dealing with time series that can be used to represent gear mesh vibrations.

$$(x_t) = \sum_{i=1}^{n} a_i\, x_{t-i} + \varepsilon_t$$

The AR model's approximation is described by the equation above, in which and stand for the data points at time and, correspondingly, represent the order model, is the AR model's ith coefficient, and represents residual error. The AR coefficients are modelled using the Yule-Walker equation so that the AR residual error only includes the gear meshing impacts. Fig. 1 displays the flow chart of the entire model.

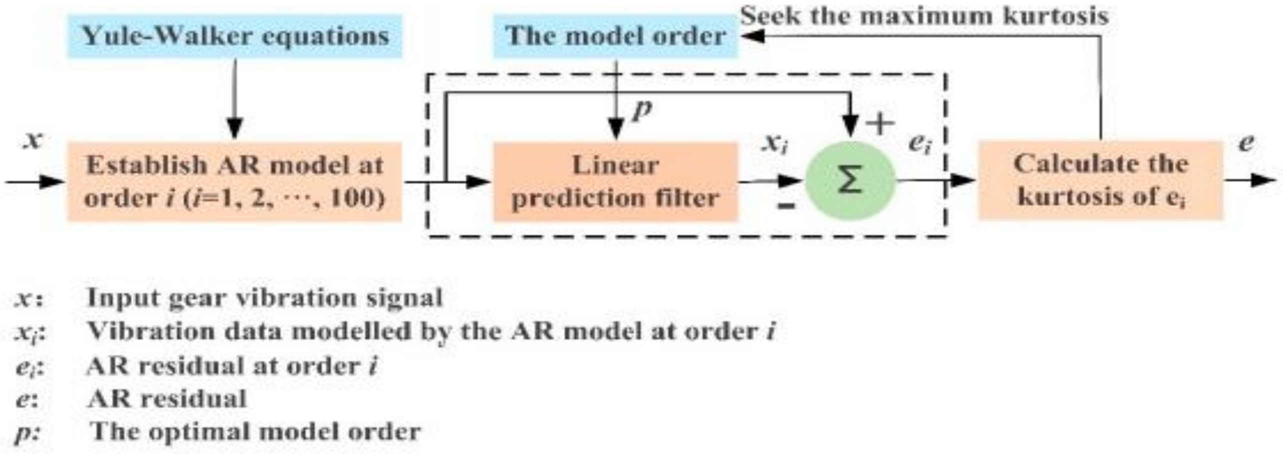

Figure 1. Flow chart of AR model [4]

According to G. Dalpiaz et al., most modern gear diagnostic techniques rely on the study of vibration signals detected by the gearbox shell. Identifying the presence and type of a problem early in its development and following its advancement are common aims for estimating the machine's remaining life and selecting a suitable maintenance strategy. Simple spectral analysis is frequently insufficient for the early detection of gear breakdown [5]. The following experimental techniques were the focus of this investigation.

1. Demodulation analysis: Analysing the amplitude and phase of the meshing signal is the basis of the signal processing technique known as demodulation analysis. The time synchronous average (TSA) must be accomplished before proceeding with the demodulation procedure. The TSA approach drastically decreases the impact of all other sources and noise by increasing the signal components caused by the relevant gear.

2. Cyclostationary analysis: A gear vibration signal's spectral structure is shaped by the interaction between its sidebands and meshing harmonics. according to cyclostationary analysis One can investigate the level of correlation, or the degree to which different frequency components of the spectrum are related to one another. Utilising Spectral Correlation Density (SCD) [5], one can investigate the connection between a meshing harmonic and one of its modulating sidebands. A gear elements sideband is many times its revolution frequency. As a result, by analysing the evolution of the gear spectrum using the SCD function, gear problems can be identified and diagnosed.

3. Cepstrum analysis: The meshing harmonics' sidebands are frequently seen in gear vibration spectra. In gearboxes that are properly maintained, the sideband level typically stays constant over time. Alterations in the quantity and strength of the sidebands usually indicate a state of decline. These sidebands are often caused, for example, when a tooth crack occurs, by the rotational frequency modulating the gear vibration. The cepstrum is helpful in deciphering the spectrum's structure and determining periodicity. The modulation time, denoted by the cepstrum peak quefrency, is reciprocal to the modulating frequency.

4. Wavelet transform: Locating broken teeth in gears is done using the Wavelet Transform technique. In fact, the demodulation method revealed that the fault hardly affected this signal. WT was applied to radial vibration in the case of a small crack size. Because crack effects are only evident in specific frequency ranges, a fault identification technique is heavily reliant on frequency selection. The presence and angular position of the fracture can only be determined by carefully inspecting the WT cross-sections.

As per Setti Suresh et al., vibration analysis is the most widely used technique for condition monitoring. The gearbox's multiple-direction accelerometer arrangement gathers the composite vibration signal, which combines the characteristic frequencies of the gear, bearing, and shaft. The UCI machine learning repository and the NREL wind turbine benchmarking gearbox datasets provided the vibration signals used in this investigation [6]. Setti Suresh et al. used supervised machine learning techniques, such as Support Vector Machine (SVM), to categorise features. Using a feature selection algorithm, the unwanted features are removed from the vector. In order to monitor the gearbox health status, three different fault classification algorithms are created and assessed. Over 100 Monte Carlo runs, the developed algorithm's accuracy in defect detection is demonstrated to be consistent.

Mahendra Singh Raghav et al. used Acoustic Emission (AE) methods to pinpoint different gearbox issues. The AE signal reflects the state of failure in the rotating machine elements in a number of important ways [7]. When using the AE approach for fault diagnosis, the parameters that are most frequently used are count, energy, amplitude, rising time, duration, and threshold. Studies show that the AE method works well for early detection of a variety of gear defects. The AE sensors will record the increasing amplitude of a gear crack or pitting. While some studies used kurtosis and crest factor approaches to identify gear failures, most researchers used Continuous Wavelet Transform, Discrete Wavelet Transform, and Empirical Mode Decomposition methodologies.

Fawzi Gougam et al. diagnosed roller bearing flaws using Time Domain Features, Singular Value Decomposition, and Fuzzy Logic Systems. By extracting Time Domain Feature data and applying Standard Deviation, Kurtosis, Entropy, and Variance, researchers can acquire defect information [8]. A matrix analysis technique called singular value decomposition can be used to find features, cut down on noise, and compress data. Set functions are used by fuzzy logic systems to generate values between 0 and 1. A fuzzy system consists of four steps: fuzzification, rules, inference system, and defuzzification, according to Mamdani's fuzzy architecture. By using fuzzy logic systems for fault classification and Time Domain Features and Singular Value Decomposition for feature extraction, Fawzi Gougam et al. developed a hybrid bearing fault detection model.

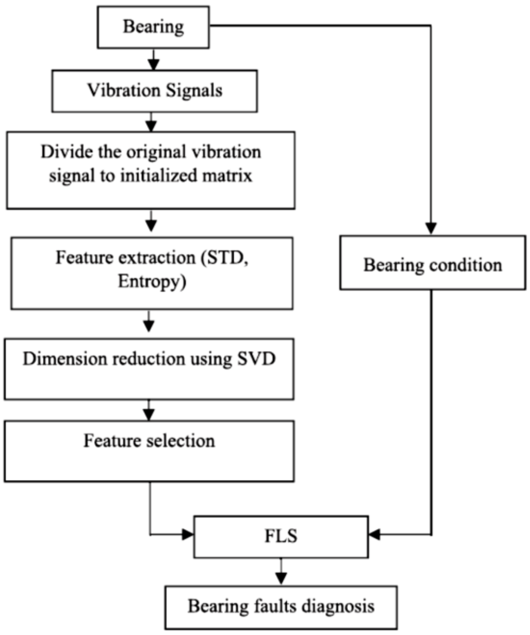

Figure 2. Proposed system model for bearing fault diagnosis [8]

Deep Recursive Dynamic Principle Component Analysis (Deep RDPCA) was employed by Huaitao Shi et al. in their study to identify gearbox problems. The steps of the Deep RDPCA algorithm are as follows: a) Convert the observation matrix into an augmented matrix; b) Update the augmented matrix with the most recent sample data; and c) Break down the updated matrix into several subspaces to identify and inform the fault data [9].

Fig. 3 depicts the Deep RDPCA model. This model's steps are as follows: Gathering the normal data (determine S), obtaining fresh sampling values (determine S+1), and reconstructing the observation value data to identify the erroneous data are the three steps in the process. Figure 4 presents the experimental results from the Deep RDPCA method for gear pitting fault identification. Figure 3: Model of Deep RDPCA [9]

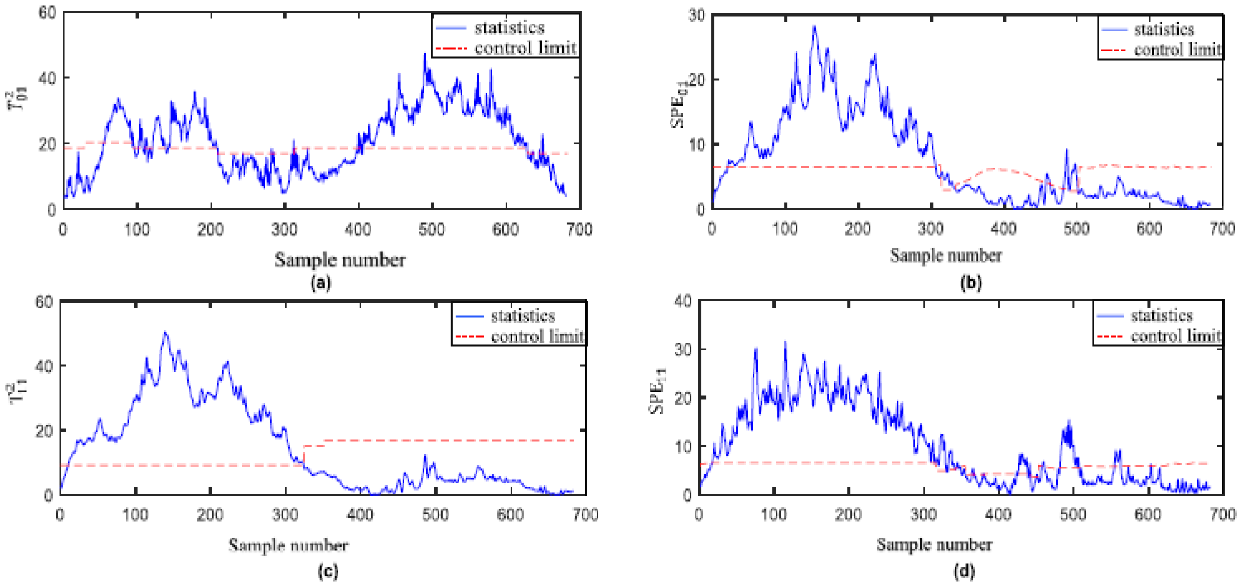

Figure 4. Experimental results of Deep RDPCA for Gear Pitting Faults [9]

Autogram analysis was employed by Adel Afia et al. to identify gearbox failure indicators. An Autogram is a refined version of the traditional Kurtogram. Kurtogram aids in the decomposition of the signal data by utilising the Maximal Overlap Discrete Wavelet Packet Transform (MODWPT) that splits the signal into frequency bands and central frequencies called nodes [10]. The greatest Kurtosis value is discovered through the impartial autocorrelation of the squared envelope method. The squared envelope is then subjected to the Fourier transform, which identifies the defective signal.In noisy environments, Autogram is a more robust signal processing technology that can extract the defect signature (Adel Afia et al. Fig. 5 depicts the autogram process's steps.

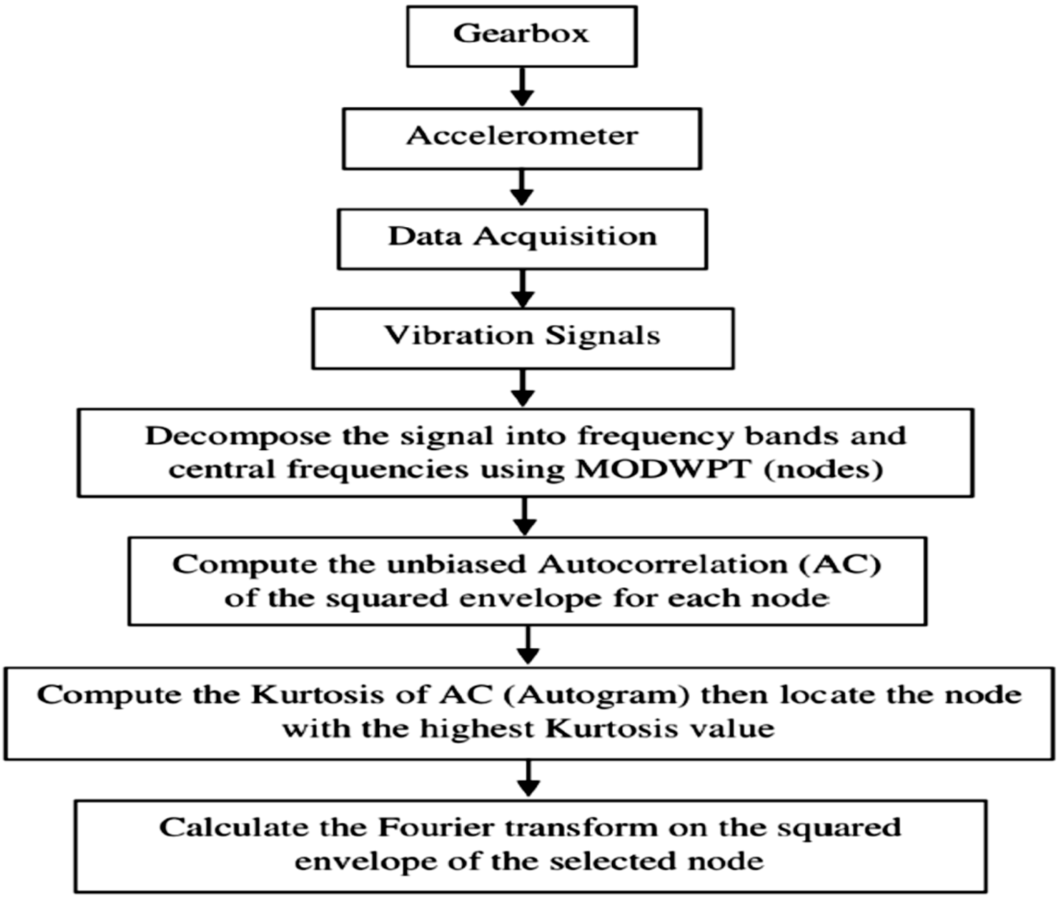

Figure 5. Steps in Autogram Process [10]

Wide frequency and very low energy compared to the total energy of the signal are two characteristics that are critical to malfunctioning equipment signals.

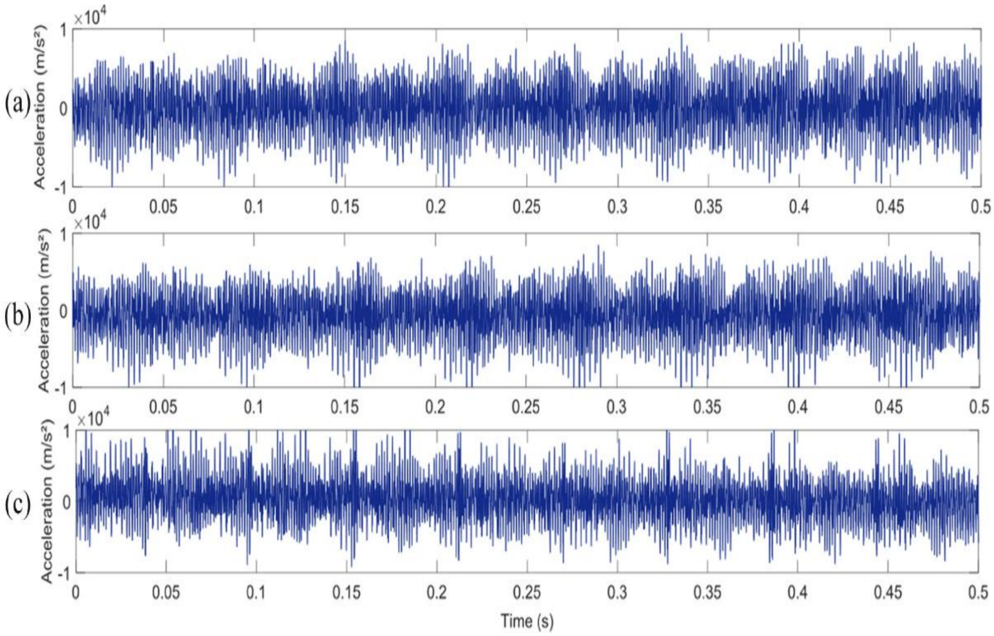

Figure 6. Vibration Signals from Chipping of Gear Tooth [10]

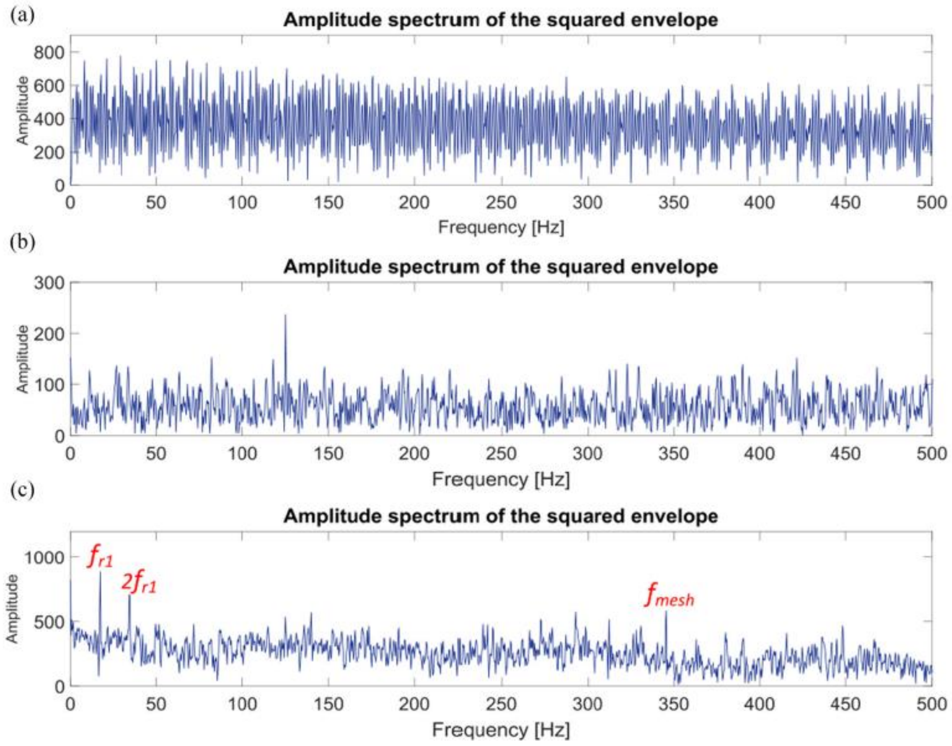

Figure 7. Spectrum obtained by Fourier Transform [10]

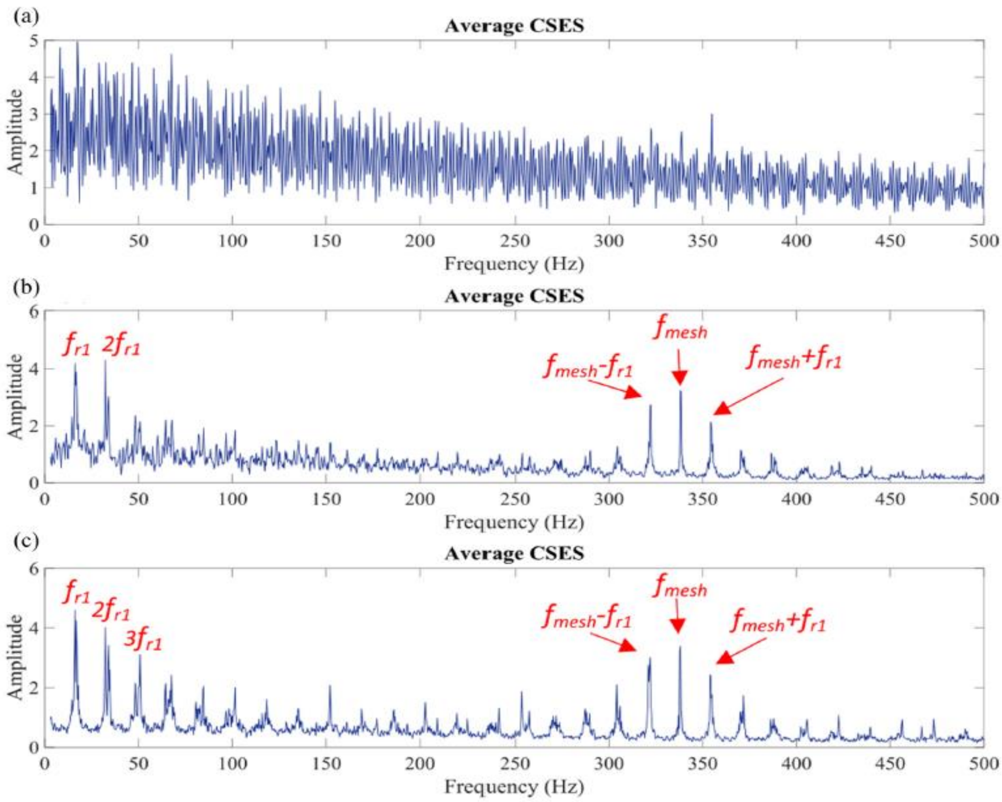

Figure 8. Spectrum obtained by Fourier Transform [10]

Figure 6 displays the vibration signals that the gearbox system sent. Adel Afia et al. claim that because the noise masks the false signals, the generated waveform cannot be utilised to diagnose gear failure. Fig. 7 displays the spectrum obtained after the Fourier Transform. As we can see, the noise level has been reduced, enabling us to identify the damaged gear. The suggested Autogram method [Figure 5] is applied to the same set of signals [10]. The squared envelope (fr1) in Fig. 8 shows the frequency modulation matching to the input shaft rotation speed. Adel Afia et al. state that the Fourier Transform can help identify gearbox issues by identifying the optimal frequency bands, and the Autogram will show the node with the highest Kurtosis value.

Berkan Hizarci et al. evaluated the worm gearbox defect's severity using vibration analysis techniques and time domain statistics. To identify faults, time domain analysis looks at the statistical characteristics of vibration signals [11]. The vibration analysis method looks for energy differences within predetermined frequency ranges to identify issues.

Figure 9 shows the configuration for the vibration analysis. The AC motor and the gearbox are connected. The flexible coupling is attached to the gearbox's output shaft.

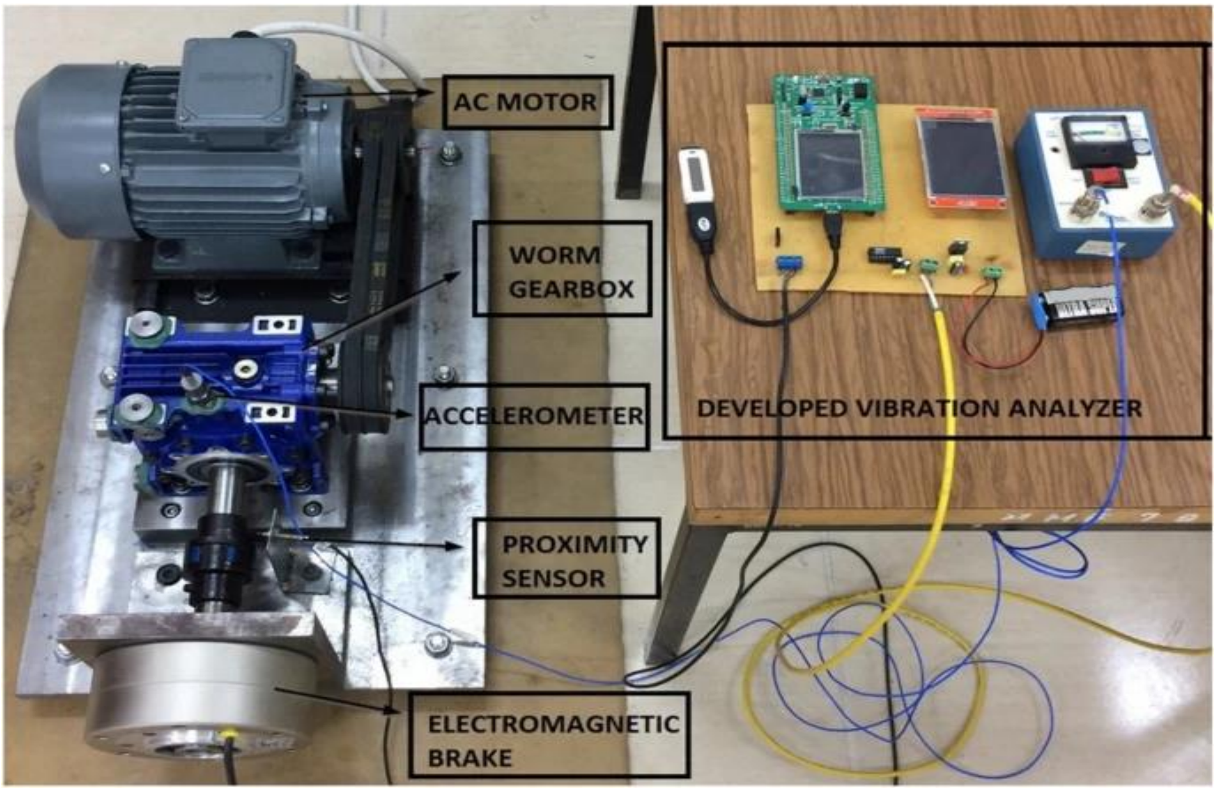

Figure 9. Experimental Setup for Vibration Analysis [11]

Piezotronics 352A76 high-resolution PCB piezoelectric accelerometers are used to measure the gearbox acceleration. A signal conditioner from the PCB Piezotronics 480C02 series is used to condition the output signals. Digital signal processing and data acquisition are performed by STMicroelectronics' STM32F429 microcontroller. The TFT displays the vibration signal analysis results, and the vibration data is saved on a USB flash drive. screen.

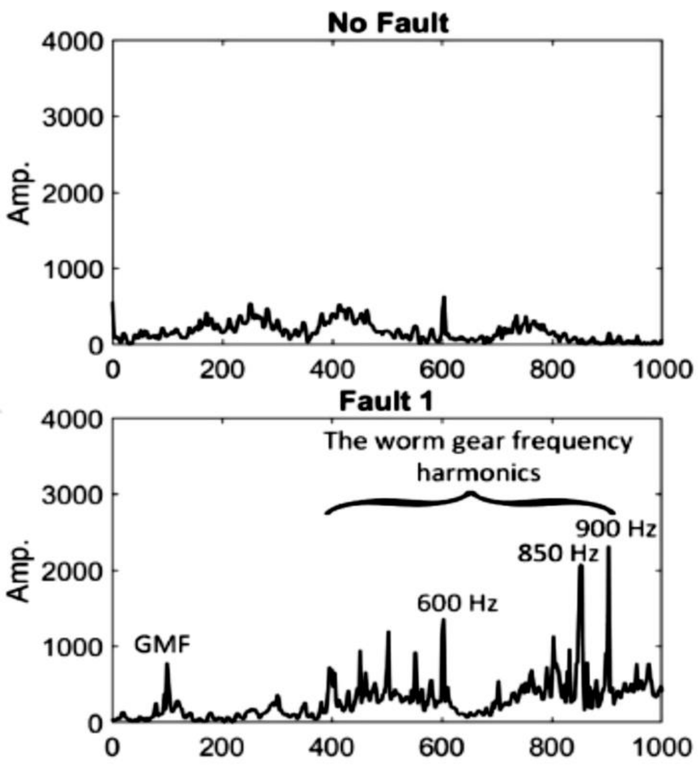

Figure 10. Frequency Signals from Vibration Analysis [11]

The frequency signals derived from vibration analysis are shown in Fig. 10. One aspect of vibration analysis is the frequency domain conversion of time domain signals. As seen in Fig. 10, Gear Mesh Frequency (GMF) is only present when there is a gearbox system issue. The severity of the fault determines the vibrations' amplitude.

Table 1. Studies related to Condition Monitoring and Signal Analysis

Author	Method	Year
Stephan Schmidt et al. [12]	Synchronous Average of the Squared Envelope method (SASE)	2020
Liu Hong et al. [13]	Fast Dynamic Time Warping (Fast DTW) and Correlated Kurtosis (CK)	2014
Ruben Medina et al. [14]	Peak Symbolic Dynamics Algorithm (PSDA)	2019
Shuiguang Tong et al. [15]	Meshing Impact Energy Distribution (MIED) approach	2019
Moncef Soualhi et al. [16]	Adaptive Neuro Fuzzy Interference System (ANFIS)	2019
Laxmikant S. Dhamande et al. [17]	Continuous and Discrete wavelet transform approach	2018
Luyang Jing et al. [18]	Convolutional Neural Network based fault diagnosis method	2017
J. Antoni et al. [19]	Cyclostationary Analysis	2002
Laxmikant S. Dhamande et al. [20]	MATLAB and Artificial Neural Network	2016
M. Saimurugan et al. [21]	Time Domain Analysis and Decision Tree Algorithm (DTA)	2016
Chao Zhang et al. [22]	Frequency Modulated Empirical Mode Decomposition (FMEMD) method	2016
X F Zhang et al. [23]	Haar-Wavelet Denoise and Fast Fourier Transform Approaches	2020
Emmanuel Resendiz-Ochoa et al. [24]	Supervised Learning and Infrared Thermography	2020
Haodong Liu et al. [25]	Variational Mode Decomposition (VMD) and Hilbert Transformation (HT) methods	2019
Nilson Barbieri et al. [26]	Wavelet Transform	2019

Few limitations of condition monitoring are discussed below

- Initial setup and equipment costs can be high.
- Requires skilled personnel for data analysis.
- False alarms or excessive alerts may lead to operational disruptions.
- Not suitable for all types of equipment or industries.
- Regular maintenance of monitoring equipment is essential.
- May not prevent all failures, especially sudden catastrophic events.

3. Conclusions

This article gives a quick introduction of the many condition monitoring and signal analysis techniques used to detect gearbox problems. The resonance-based signal sparse decomposition (RSSD) method is widely used for evaluating the effects of gear meshing and engine ignition. The amplitude changes of each gear element in the gearbox can be tracked using methods like Cepstrum analysis and Spectrum Correlation Density. The most popular application of the Support Vector Machine (SVM) algorithm is feature classification. The model is trained using 70% of random permutation observations. In Acoustic Emission (AE), a non-destructive method, an AE sensor is used to detect the displacement of the sensor as Rayleigh waves pass through a material surface. Surface attenuation is this technology's primary drawback. When it comes to defect detection, especially in rotating machinery, the Fuzzy Logic System (FLS) is the most efficient method that doesn't require a big database. The technique known as Deep Recursive Dynamic Principle Component Analysis, or Deep RDPCA, is used for real-time monitoring of nonlinear dynamic systems. By reducing noise components, the autogram method can identify gear defects from raw data. Time domain analysis indicates that the degree of flaws affects the vibration signal's RMS and mean frequency.

Competing Interests

The authors have declared that no competing interests exist. Date Availibility Statement All date are in the manuscript and/or supporting information files.

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