Analysis of Faults and Dominating Abnormalities in Roller Bearing Elements Under Varied Operating Conditions: A Review

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A safe and efficient operation depends on the reliable operation of bearings, which are essential components of industrial machinery. The present set of investigations examines a variety of bearing behavior, defects, and vibrations issues, providing out crucial information for the machinery's reliability and maintenance. A wide range of working situations, including different load levels, speeds, defect kinds, and defect sizes, are considered in the analysis. Numerous procedures and techniques are used to study and diagnose defects in various types of bearings. Predictive maintenance's function in reducing downtime and enhancing bearing performance, as well as the significance of early preventative maintenance based on early failure detection, are also emphasized. Further to improvements in condition monitoring tools like vibration analysis, acoustic emission, and others. The analyses use a variety of methodologies, including experimental research, data analysis, and applications of machine learning. The deployment of most AI systems is severely constrained since they require a significant number of data that must be labeled for both normal and abnormal conditions and lack explainable ability attributes.

1. Introduction

A machine system's safety and dependability are significantly influenced by rolling element bearings. Among the greatest engineering innovations of the modern era is the bearing, which is essential in reducing wear on any rotating device. There are three primary types of bearings: roller, ball and bushed bearings. Tapper bearings are the most frequently utilized bearing due of its high capacity and reliability. [2] As seen in Fig.1, a rolling bearing normally consists of three components: rolling elements, an inner race, and an outer race.

Fig. 1. Taper Rolling Bearing

These three parts are susceptible to a variety of issues, including faulty mounting, inadequate lubrication, and the passage of foreign particles. Due to design error, mass unbalance, looseness, bending, misalignment, rub, improper assembly operation, and resonance, several common faults are also introduced in rolling element bearings. The Electric Power Research Institute's failure studies show that among the most common errors in induction motors, bearing defects account for around 40% of all failures. [9] To make sure the efficient functioning of industrial equipment, a variety of maintenance strategies, among the often employed techniques in the industries are condition-based, predictive, preventive, and corrective maintenance. [3] The initial three steps in fault diagnosis are ascertaining the equipment's normal operation, locating the impending breakdown and its cause and identifying the fault development trend. [10]

Rotating machinery diagnostics has been investigated using AI approaches. The theoretical foundations and practical application perspectives of ANN, K-NN algorithm, SVM and other deep learning-based defect detection techniques for rotating machinery have been presented. AI methods is frequently utilized because of its established performance and ability for developing data-driven operational and planning strategies from industrial data. [3]

Different bearing parts might acquire faults for a variety of reasons. Finding the precise source of bearing failures is challenging. Moreover, one or more of the following causes can lead to bearing damage as shown in Table 1.

Table I. Rolling element bearing failure modes

Mode of Failures	Causes of Failures
Fatigue	The rolling component experienced repeated stresses.
Wear	Causes due to lack of lubrication.
Contamination	Causes due to enter of foreign matter into cleaning agents or lubricants.
Excessive Loads	Causes due to the overloading of axial and thrust loads.
Lubrication Failure	Causes due to inadequate lubrication, poor lubricant selection, and high temperatures that cause lubricant degradation.
Corrosion	Because of the relative movement between races and the shaft or housing and the looseness of the rolling components.

Plastic Deformation	Causes due to improper attachment of rolling parts, rings, seals, or shock loading.
Overheating	Usually, it is caused by incorrect lubrication and high operating temperatures.
Misalignment	Include due to twisted shafts from loose fittings, malformed spacers, deformed shaft shoulders, and clamping nuts.
Fit	Causes due to the close fit, an overloaded condition will exist for the bearing.

2. Literature Survey

Linkai Niu et al utilizing dynamic modeling and experimental data to examine the vibration qualities of a cylindrical roller bearing with roller faults. Initially, a test was done to count the impulses generated while a roller faults rounds a race. Next, a vibrant model was proposed for cylindrical roller bearings with roller faults, considering factors such as corresponding slippage, a roller's finite size, and the direction shift of the contact force. As can be observed in Fig. 2, when a roller defect surrounded the outer and inner races, the bearing's vibration responses were investigated using the recommended dynamic model. The effects showed that, in addition to the impulses generated when the roller edges roll through the line connecting the roller and race centers, there could be further impulses generated by the interaction between the roller fault and the race. Additionally, the study found that when the radially loaded cylindrical roller bearing rotates in the loaded zone, the roller fault impacts both the inner and outer races, but only the outer race when it is in the unloaded zone. The roller fault interacted with the inner race for a longer period of time on average than it interacted with the outer race. [1]

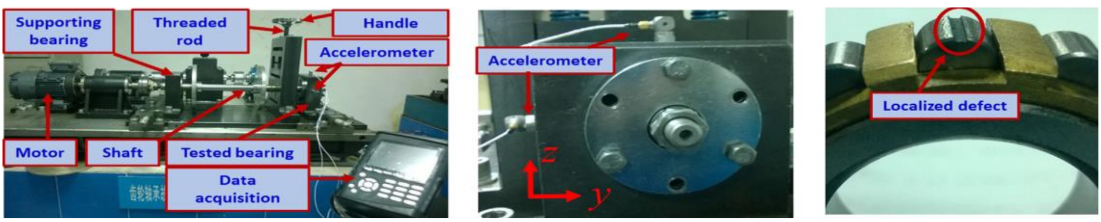

Fig. 2. Setup for the experiment (a) Test apparatus. (b) Accelerometer sensor. (c) Roller faults [1]

J.J. Jayakanth et al illustrates method to examine ball bearings using the gryndosonics technique, focusing on finding faults in both the inner and outer races as shown in Fig. 3. This method appears to rely on the examination of amplitude waveforms and power spectrum in order to identify irregularities and variations from typical patterns related to new and effective bearings. [2]

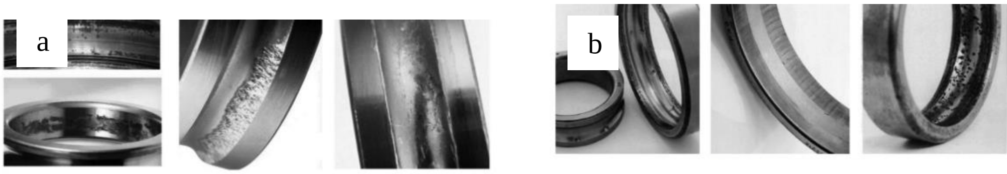

Fig. 3. (a) Inner race defect of the ball bearing; (b) Outer race defect of the ball bearing. [2]

Waqar Muhammad Ashraf et al combines data analysis, support vector machine (SVM) and artificial neural network (ANN) models, and the practical implementation of these methods to lessen vibration in a steam turbine's bearing. Particularly in a high-capacity supercritical steam turbine system, the decrease in vibration is viewed as a means of preventing downtime, expensive maintenance, and ensuring the secure and ongoing functioning of the equipment. When the load grew from the various range, the relative vibration of the steam turbine shaft's bearing decreased by 4.07%. [3]

Madhavendra Saxena et al concluded that the main factor in the failure of ball and cage corrosion is pitting. The main emphasis was on bearing defects and the application of most effective technique called Continuous Wavelet Transform (CWT) for the subsequent analysis of vibration data as shown in Table 2. As a tool for classifying different bearing defect types, such as inner, outer race faults, or other issues, the unique CWT signatures discovered through this investigation are used. These defects can be created by a number of methods, such as electrical discharge machining (EDM) and corrosion caused by contact with an acidic solution. [4]

Table II. Comparison of a Signals [4]

Method	Domain	Features
RMS	Time	Compared to frequency resolution, the time resolution is better.
Kurtosis	Time	Sensitive to impulsive and transient signals, it works perfectly for detecting localized faults but is less useful for steady-state or low-impact problems.
Fourier	Frequency	In contrast to frequency resolution, the time resolution is weak.
STFT	Time-Frequency	Both the time and frequency domains are concurrently resolved. However, their resolution is set.
Wavelet	Time-Frequency	Time resolution is strong in low-frequency regions but poor in the frequency domain. Time resolution is strong but frequency resolution is poor in high-frequency zones.

Sudhakar. I et al investigated the significance of proactive maintenance and monitoring to find and fix problems before they become serious. The motor's performance must be maintained in order to avoid expensive breakdowns. On the drive end side of the three-phase induction motor with deep groove ball bearings, a fault on the cage was discovered in its beginnings. The FFT spectrum analyzer produced the vibration and time wave patterns after converting the measured acceleration by the accelerometer into impulses. The underlying principle for diagnosing an induction motor was a concept of vibration excitation. The axial and radial spectrum which are recorded on the bearing at regular intervals of time. So, it requires replacing the damaged bearing and correcting misalignment. [5]

Surojit Poddar et al uses Acoustic Emission and Vibration Analysis to look at the impact of particle contamination on journal bearings. It describes how particle size and concentration affect these responses and describes the distinctive variations in the Acoustic Emission and vibration spectrum that take place during three-body abrasion. In order to provide a thorough explanation of the phenomenon, the study uses numerous tests with different particle sizes (10 um, 30 um, 50 um, and 70 um) and twelve distinct concentrations. It has been discovered that when particle size and concentration rise, vibration in terms of velocity also increases. However, no significant difference in vibration is seen for particles smaller than 10 μm. [6]

Sujeong Baek et al developed method to identify mechanical system failures, this method combines semi-supervised classification and pattern extraction from multivariate sensor signals. It emphasizes the method's ability to find instructive patterns even with scant label data available, which helps to increase fault detection performance. As a result of its successful detection performance, it directs attention to the need for additional research to overcome several drawbacks and improve the application's perspectives, including early deterioration detection and unsupervised solving issues. [7]

Khadersab Adamsab presents a thorough analysis of machine learning methods and algorithms used to detect bearing problems in rotating machinery. With the ultimate goal of enhancing machine dependability and performance, it compares various strategies based on both their theoretical basis and their actual practical use in industrial applications. A focus on early fault diagnosis and condition-based maintenance in mechanical systems drives as shown in Fig. 4 the evaluation of the effectiveness of Support Vector Machines, K-Nearest Neighbor, Artificial Neural Networks, Relevance Vector Machine, and other techniques. [8]

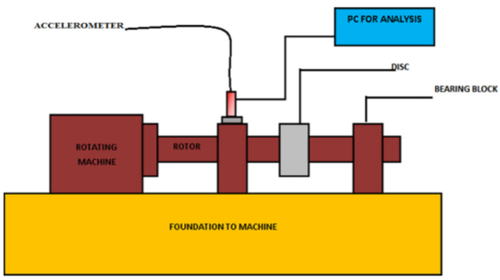

Fig. 4. Important location of measurement for defects in rotating machinery [8]

Jaouher Ben Ali et al describes a thorough technique for the condition tracking and rolling element bearing problem diagnosis with an emphasis on the use of artificial neural networks, energy entropy, and empirical mode decomposition. The method has been demonstrated to be efficient in identifying problems and determining the state of monitored bearings, potentially minimizing the requirement for human intervention in determining the health of machinery. For predictive maintenance and determining the useful life of bearings, the proposed health index shows potential in identifying bearing damage early. Expanding the model's capacity to manage varying operational conditions may be a part of ongoing effort. [9]

Lucas C. Brito et al investigated the essential function of monitoring rotating machinery, highlighting the demand for knowledge in deep learning-based fault detection and diagnostic systems. The three primary parts of the suggested method are feature extraction, defect identification, and problem diagnosis. The approach further advances the field of fault identification by analyzing a number of cutting-edge defects detection methods in the context of rotating machinery. [10]

Ganesh L. Suryawanshi et al examined the intricate dynamics of rolling element bearings, focusing in particular on the potential consequences of inclined surface flaws stemming from frequent variations in load and speed in high-speed rotating equipment as shown in Fig. 5. [11]

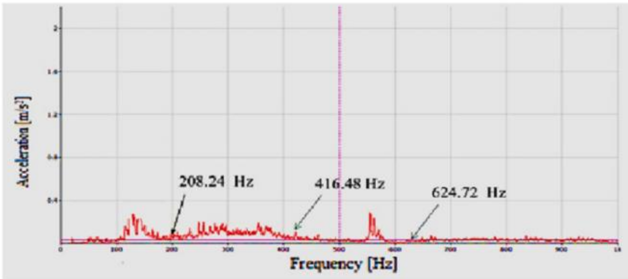

Fig. 5. Vibration response of good condition bearing at 1000 rpm. [11]

Shuai Gao et al. investigated a complex Ten degree of freedom non-linear vibrant model with exact forms of communication between Three Dimensional cubic-like defects in an angular contact ball bearing is offered to examine the static and dynamic behavior. In order to decrease the amplitude and length of the vibration, the flaw should not be extended in a circumferential direction; nevertheless, by extending the defect axially, the bearing system's vibration can be made to vibrate less intensely. [12]

Anil Kumar et al. using symmetric single-valued neutrosophic cross-entropy of Variational Mode Decomposition, a new method of automatically identifying faults that also increases accuracy is used in the Deep Groove Ball Bearing of a centrifugal pump. [13]

Jing Liu et al advised to make use of an enhanced time dependent displacement excitation (TDDE) model in order to account for localized bias, offset, or parallel faults in the outer race of the ball bearing. The TDDE model for the parallel, offset, and bias defect cases is constructed using a piecewise function model that includes the rectangle and half-sine functions. The Hertzian contact theory is utilized to compute the bearing contact stiffness. The consequences of fault diameters, defect offset distance, and defect bias angle on vibrations in ball bearings are analyzed. The results indicate that the proposed method can provide a more accurate and rational analytical approach to vibration analysis of ball bearings with local offset problems. [14]

Sameera Mufazzal et al developed method to using a modified 2-degree of freedom (DOF) lumped parameter model, the process digs into an extensive analysis of ball bearings of the vibration responses. To accurately replicate the behavior of both good and defective bearings under a range of velocity and load situations, the model also adds additional deflection and multi-impact theories. This technique emphasizes the complexity of bearing vibrations and the possibility that compliance-induced impulses could be misconstrued for bearing flaws. It underlines the significance of a sophisticated and knowledgeable approach to fault diagnosis and defect size assessment, taking into account many affecting elements. The procedure advances knowledge of bearing behavior and provides information that can increase the accuracy of bearing diagnostics and maintenance choices. [15]

Chengwei Wena et al presents valuable details about the complex dynamics of angular contact ball bearings with localized faults. It provides insight on the bearing behavior in conditions of high speed by considering into account multi-DOF interactions and modeling imperfections in the geometrical restrictions. For mechanical equipment to operate safely and reliably, it is essential to comprehend how defects affect load characteristics, angular misalignments, and other variables. [16]

Ali Moshrefzadeh provides a cutting-edge method called Spectral Amplitude Modulation to solve the difficulty of identifying bearing health under various working circumstances. To provide intelligent diagnosis and condition monitoring, the system uses impulsive and machine learning algorithms. The method's potential for use in real-world applications is demonstrated through experimental validation using multiple test rigs and different kinds of faults. The proposed technique is known as "SKC," which is derived from the initial initials of SAM, Kurtosis, and Classification. It is intended for online condition monitoring and intelligent diagnostics of rolling element bearings, with an emphasis on resolving issues linked to fluctuating operational situations. The suggested approach shows promise for industrial applications, and experimental findings illustrate its usefulness in classifying different types of bearing failures. [17]

A. Srivania et al. propose a simple time domain-based technique employing the Fourier harmonic regression analysis method for deep groove ball bearing condition monitoring. It was discovered that for no-fault conditions, a distinct repeating trend with a dominating fifth harmonic is obtained and that fluctuations are stronger for ball faults because of the ball's random rotation during bearing rotation. [18]

Deqiang Tan et al provides information of wear-related failure of the joint bearing in the main rotor of the Robinson R44 helicopter. It highlights the need of managing fabric liner damage and PTFE transfer film formation to improve the dependability and safety of helicopter operations and discusses important wear mechanisms. Several analysis techniques were used in the study, including stereo microscopy, scanning electron microscopy, energy-dispersive X-ray spectroscopy, electron probe microanalysis, and X-ray photoelectron spectroscopy. [19]

Xueqin Hou et al presents valuable details about the high axial force used during tightening had been responsible for the premature failure of the cylindrical roller bearing since it caused deformation and uneven contact stress. In order to avoid repeat failures, the study focuses on axial force management, bearing component design improvement, and stress concentration minimization. These steps are intended to increase the dependability and lifetime of the bearings already in use. [20]

A. Galezia et al introduces the Multiband Demodulation Analysis (MDA) method of rolling element bearing condition monitoring. MDA has the potential to aid in early failure detection and diagnosis by examining vibration signals across a range of frequency bands and isolating key modulation components. The results of the study demonstrate the potential of MDA as a useful tool for boosting the safety and reliability of rotating machinery. [21]

Yulong Ying et al investigated a precise evaluation of rolling bearing faults in real time is made possible by the suggested fault diagnostic approach. Its usefulness is demonstrated by the high success rates at determining the types and severity of faults. Additionally, the analysis shows the potential for future research to incorporate cutting-edge signal processing techniques to further improve fault detection accuracy, making it a useful tool for condition monitoring and maintenance in many industrial applications. The suggested approach's diagnostic results show a high success rate for identifying bearing faulty circumstances, with a total fault pattern recognition success rate of around 97%. The method's dependability in real-world applications is suggested by its high success rate. [22]

Yi Qin et al enhances the understanding of the dynamic behavior of rolling bearings with localized defects by creating a complex multiple-degree-of-freedom fault dynamic model. The credibility and usefulness of the model are increased by combining dynamic simulations with experimental validation. Future work on high-speed rolling bearing defect identification and prognosis will increase safety and dependability in a variety of industrial applications. [23]

Vivek Parmar et al recommended to us for better understand how self-aligning rolling-element bearings behave dynamically when they have localized flaws in dynamic misalignment settings. The results highlight the significance of taking into account load circumstances, defect dimensions, and misalignment when examining the vibration response of such bearings. The study shows that the behavior of spherical bearings is affected differently by radial and axial loads. For both rows of rolling elements, an increase in radial load tends to increase the contact force and acceleration response. However, when axial load increases, each row responds differently. This is due to the fact that axial load causes the rows to shift axially, which changes the effective outer-race diameter uniquely for each row. [24]

Ying Zhang et al presented fault diagnosis approach efficiently analyzes no stationary vibration signals by combining Enhanced Empirical Mode Decomposition, singular values, Kernel Principal Component Analysis , Particle Swarm Optimization, and Support Vector Machines. In order to locate faults and gauge the severity of performance degradation in roller bearings, it overcomes difficulties brought on by nonlinearity and non-stationary and provides better identification rates and generalization capabilities. This technique has the potential to be a useful tool for applications involving machinery health monitoring and predictive maintenance. [25,30]

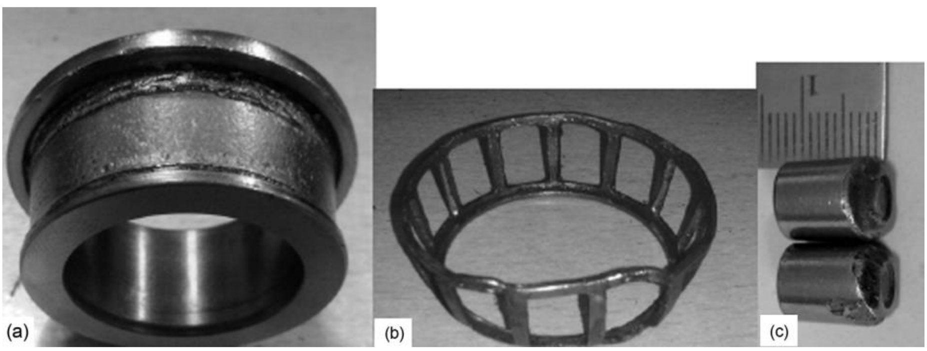

Fig. 6. Premature failed bearing in as-received condition: (a) deep groove on the raceway of the cone; (b) distorted cage; (c) severely damaged tip at one side [30]

3. Methodology

System architecture should have been developed for various failures in rolling element bearings. It is necessary to identified for verifying dominating abnormalities responsible for faults in rolling element bearing. Most of the models proposed by researchers have concentrated on a single defect. Very few method is available on combined localized faults in rolling [illegible]ment bearing. For this, it is necessary to create an experimental setup as shown in Fig. 6 (a [illegible]or evaluating various defect-free and faulty bearings at various speeds, loads and types of defects.

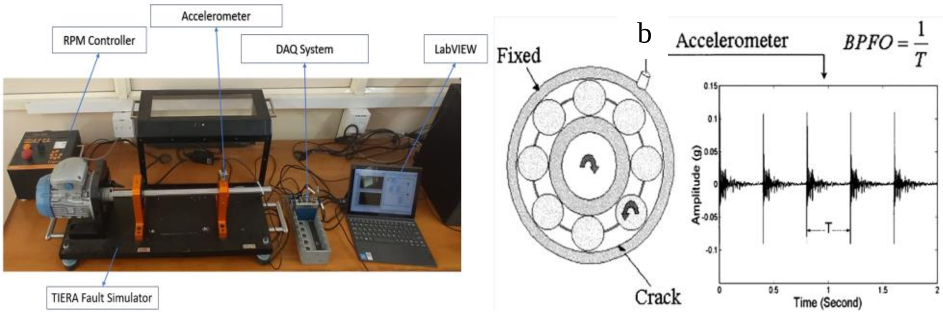

Fig. 7. (a) Proposed Experimental Setup; (b) Vibration signal plot, amplitude as a function of time of a bearing shows ringing excitation due to fault in the outer bearing race. [2]

This system's peculiarity lies in its capacity to detect bearing faults such as inner race, outer race, ball or roller, and cage faults. The bearing analysis methodology consists of the following steps:

3.1 Data collection

This includes gathering information on the bearing's operational circumstances, such as temperature, speed, load, and lubrication. To assess the bearing's condition, vibration and acoustic information can also be gathered [3].

3.2 Artificial faults

Utilizing Electrical Discharge Machining (EDM), the experimental design uses tapered roller bearings with predetermined defects in three geometries: circular, square, and line. In order to examine how bearing performance is affected by several characteristics, including rotational speed, radial load, and imbalance, the study employs a rigorous Design of Experiments (DOE) technique.

Fig. 8. (a) Artificial faults by EDM machine ; (b) Line defect and Circular defect. [26]

3.3 Signal Processing, Fault Detection, Diagnosis, and Prognosis in Bearing Fault Analysis

In order to extract relevant information from the acquired vibration signals, kurtosis is a metric that is especially crucial for detecting abnormalities in signal behaviour. The signals are analysed using methods like Wavelet Transform, Empirical Mode Decomposition (EMD), and Fast Fourier Transform (FFT). Faults are identified by analysing the processed data and looking for signs such sidebands, changes in frequency content, and increased vibration amplitude. Once a fault has been identified, its type, location, and severity are diagnosed, providing information about the defect's characteristics, such as wear, corrosion, or cracking. The bearing's remaining usable life is finally predicted using sophisticated techniques like Artificial Neural Networks (ANN), which makes proactive maintenance planning easier.

4. Conclusion

Numerous investigations concentrate on specific techniques for detecting bearing faults, like vibration analysis or machine learning. However, research must investigate the integration of many approaches to improve diagnostic accuracy and reliability in order to produce more comprehensive and precise detection systems. Prioritizing real-time monitoring and quick identification of defects in industrial settings may significantly improve maintenance strategies, maximize operational effectiveness, and reduce unexpected downtime. The combined use of modern signal processing techniques, statistical methodologies, and machine learning models holds enormous promise to improve fault diagnosis, enabling for more adaptable and precise fault detection systems.

It is crucial to conduct comparative studies with benchmark datasets in order to properly evaluate how effectively alternative detection algorithms work. In addition to defining best practices, these studies identify the most effective strategies for particular applications and operating circumstances. Furthermore, the methodical assessment of various fault detection approaches in a controlled setting could identify faults in current techniques and open an opportunity for innovative solutions.

Even though there are a number of methods to diagnose bearing failures, more accurate approaches are still required in order to consistently identify problems in their early stages, long before machinery failures occur. To collect data from bearings in a variety of situations, including those in good condition and those displaying specific defects such outer race faults, inner race faults, and defective balls, experimental investigations must be carried out using consistent control parameters. Defects in the forms of circles, squares, and lines can be purposefully introduced to provide important information about how they react dynamically under different operating circumstances.

Particularly, kurtosis shows to be a crucial bearing health indicator, efficiently detecting abnormalities in vibration signals and providing information about the type and extent of the fault. Researchers can increase the precision and dependability of diagnostic systems by concentrating on this statistic in addition to other important factors. Developing techniques to record and examine the dynamic responses of rolling bearings with many localized defects is also crucial. These developments will have a major impact on the creation of reliable fault detection systems which ensure the durability, safety, and effectiveness of industrial equipment.

Acknowledgements

The authors are thankful to the Management and Principal of Matoshri College of Engineering & Research Centre, Eklahare, Nashik for providing the relevant resources in carrying out the research.

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