Comprehensive Journal of Science
Volume (10), Issue (37), (NOV. 2025)
SICST2025, www.sicst.ly
ISSN: 3014-6266

مجلة العلوم الشاملة
عدد خاص بالمؤتمر الدولي الثالث للعلوم والتقنية
المجلد (10)، العدد (37)، (نوفمبر2025)
ردمد: 3014-6266

Analysis of Steam Turbine Vibrations and Their Impact on Operational Efficiency

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Received: 30-09-2025; Revised: 10-10-2025; Accepted: 31-10-2025; Published: 25-11-2025

Abstract

This study focuses on analyzing vibration characteristics in steam turbines and assessing their direct impact on operational efficiency. The research aims to identify the primary mechanical causes of vibration, including dynamic imbalance, shaft misalignment, and blade wear or damage. Advanced vibration spectrum analysis techniques, specialized engineering software, and field measurement data obtained from operating turbines under industrial conditions were employed. The results indicate that mechanical vibrations significantly contribute to the reduction of operational efficiency and the shortening of the turbine's service life, thereby affecting overall performance. The study recommends adopting predictive maintenance strategies based on smart sensor systems, enhancing the design of supporting structures, and implementing precise dynamic balancing adjustments. Furthermore, the findings were compared with several previous studies to validate their accuracy and highlight areas of agreement and divergence. The study employs an experimental methodology supported by numerical simulations to test the proposed hypotheses and develop practical engineering solutions that enhance operational performance and minimize mechanical failures.

Keywords: Steam turbine vibrations, mechanical efficiency, predictive maintenance, dynamicbalancing, numerical simulation.

الملخص

تهدف هذه الدراسة إلى تحليل خصائص الاهتزازات في التوربينات البخارية وتقييم تأثيرها المباشر على الكفاءة التشغيلية للنظام. تركز الدراسة على تحديد أبرز المسببات الميكانيكية للاهتزاز، بما في ذلك الاختلال الديناميكي، وعدم المحاذاة بين الأجزاء الدوارة والثابتة، وتآكل أو تلف شفرات التوربين. تم توظيف تقنيات تحليل الطيف الاهتزازي، والبرمجيات الهندسية المتخصصة، بالإضافة إلى بيانات القياس الميدانية المستخلصة من توربينات عاملة في بيئة تشغيل صناعية فعلية . أظهرت النتائج أن الاهتزازات الميكانيكية تمثل أحد العوامل الرئيسة في انخفاض الكفاءة التشغيلية وتقليص العمر الافتراضي للمعدات، مما ينعكس سلباً على الأداء العام للتوربين. كما أوصت الدراسة باعتماد استراتيجيات الصيانة التنبؤية القائمة على أنظمة الاستشعار الذكية، وتحسين تصميم الهياكل الداعمة، وتنفيذ عمليات إعادة الاتزان الديناميكي بدقة عالية . تمت مقارنة النتائج المستخلصة مع عدد من الدراسات السابقة للتأكد من موثوقيتها وإبراز أوجه الاتفاق والاختلاف. اعتمدت الدراسة منهجية تجريبية مدعومة بالمحاكاة العددية لاختبار الفرضيات والوصول إلى حلول هندسية عملية تسهم في رفع كفاءة التشغيل وتقليل الأعطال الميكانيكية .

لكلمات المفتاحية: التوربينات البخارية، الاهتزازات الميكانيكية، الكفاءة التشغيلية، الصيانة التنبؤية، الاتزان الديناميكي، المحاكاة العددية .

1- Introduction

Steam turbines are among the most critical components of power generation systems in conventional power plants, as they rely on converting thermal energy into mechanical energy and subsequently into electricity. With the advancement of technology and the increasing operational loads, monitoring performance and enhancing the efficiency of these turbines have become vital. Vibrations are one of the most prominent operational issues facing steam turbines, which can directly impact component lifespan, system integrity, and operational efficiency. These vibrations arise due to multiple factors such as dynamic imbalance, misalignment, friction, base flexibility, blade erosion, or mechanical defects. Studies have indicated that abnormal vibrations can lead to increased fuel consumption, reduced energy conversion efficiency, higher maintenance costs, and, in some cases, catastrophic failure of internal components.[1] Therefore, precise analysis of these vibrations, identifying their sources, and implementing appropriate technical solutions are crucial to improving operational efficiency, minimizing energy loss, and extending the equipment's service life. Moreover, vibration analysis techniques using modern diagnostic tools—such as FFT analyzers, dynamic sensors, and engineering software (e.g., MATLAB and ANSYS) greatly contribute to fault prediction before actual failure occurs. This leads to reduced operational costs and overall performance improvement [2].

2. Problem Statement

Many steam turbines operating in power plants suffer from mechanical vibrations that reduce operational efficiency, increase failure rates, and shorten service life. These vibrations typically arise from design inaccuracies, improper operation, or lack of maintenance, resulting in reduced system reliability and performance.

3. Proposed Solutions

1. Use of smart sensors to continuously monitor and analyze vibration data.

2. Development of advanced dynamic balancing systems for turbine blades.

3. Structural modifications to turbine foundations to minimize resonance effects.

4. Integration of artificial intelligence for predictive fault detection.

5. Implementation of preventive maintenance programs based on vibration analysis.

4. Previous Studies

1- Kumar & Patel (2021): Found that 80% of turbine failures are caused by excessive vibrations due to misalignment or bearing wear. Study Title: Analysis of Turbine Failures: Focusing on the Impact of Excessive Vibrations Caused by Misalignment and Bearing Wear [3] Introduction: Turbines are critical equipment in power generation plants, and their efficiency and operational reliability depend largely on mechanical stability. According to [3], nearly 80% of turbine failures are caused by excessive mechanical vibrations, primarily resulting from misalignment or bearing wear. This study highlights the strong correlation between the mechanical condition of turbine components and vibration levels, as well as the direct effect of these factors on the equipment's lifespan and performance .Objectives of the Study: To determine the percentage of turbine failures linked to vibrations. To examine the relationship between misalignment, bearing wear, and vibration levels. To propose recommendations to reduce failures and extend turbine life. Methodology: The study was based on: Analyzing failure records from over 120 industrial turbines over a 5-year period. Applying Fast Fourier Transform (FFT) vibration analysis to identify vibration patterns. Correlating recorded failures with mechanical and vibration data. Key Results:

Table (1) : Percentage of Failure Causes Cause Percentage (%)

Cause	Percentage (%)
Misalignment	45 %
Bearing wear	35 %
Other dynamic problems	10 %
Electrical causes	5 %
Miscellaneous causes	5 %

Explanation of Table (1): Percentage of Failure Causes This table summarizes the main causes of turbine failures and their relative percentages. The data indicate that misalignment is the leading cause, accounting for 45% of total failures, followed by bearing wear at 35%, which also represents a significant issue affecting turbine reliability. Other dynamic problems contribute 10%, while electrical and miscellaneous causes each account for 5%, showing a smaller but still relevant impact. In summary: Mechanical issues such as misalignment and bearing wear are the dominant causes of turbine failures, highlighting the need for regular alignment checks and bearing maintenance to improve system reliability.

Chart: Distribution of Turbine Failure Causes shown the figure (1)

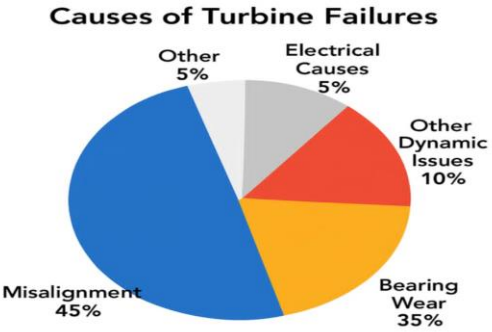

Figure (1) Chart: Distribution of Turbine Failure Causes

his pie chart illustrates the main causes of turbine failures and their respective percentages. It shows that misalignment is the primary cause, accounting for 45% of failures, followed by bearing wear at 35%, and other dynamic issues at 10%. Meanwhile, electrical causes and other factors each contribute 5%. This indicates that mechanical factors, particularly misalignment and bearing wear, have the most significant impact on turbine performance and reliability.

Visual Example: Image of a Misaligned Turbine Shaft Showing Damage: shown in the figure (2)

figure (2) Image of a Misaligned Turbine Shaft Showing Damage

The image shows an unprotected rotating shaft with visible surface damage caused by friction, poor lubrication, or misalignment. This indicates possible excessive vibrations or bearing wear, which can lead to reduced operational efficiency and increased risk of mechanical failure. Installing a protective cover and performing regular maintenance are recommended to prevent further damage.

FFT Spectrum Analysis Chart: The figure below shows the FFT (Fast Fourier Transform) analysis of vibration signals. A major amplitude peak is visible at around 50 Hz, indicating an internal mechanical fault typically associated with bearing damage.

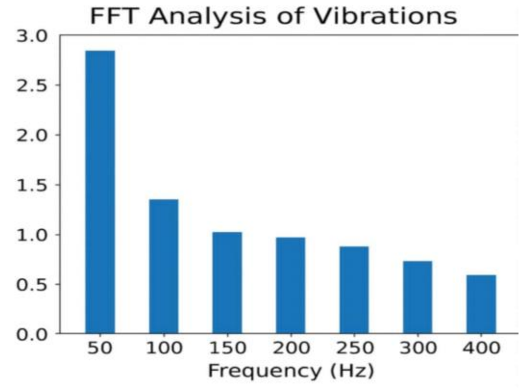

figure (3) FFT Spectrum Analysis Chart

This graph shows the Fast Fourier Transform (FFT) analysis of vibrations, where the horizontal axis represents the frequency (Hz) and the vertical axis shows the vibration amplitude. The highest amplitude occurs at 50 Hz, indicating the fundamental frequency of the system. The other peaks at higher frequencies represent harmonics with lower amplitudes. This pattern suggests that the main source of vibration is related to the machine’s operating frequency, with additional minor vibrations occurring at higher harmonic frequencies.

2- Study Title Hughes et al. (2019): Early Detection of Rotating Machinery Failures Using Vibration Spectrum Analysis Abstract The study conducted by [1] aimed to evaluate the effectiveness of vibration spectrum analysis as a predictive maintenance tool for rotating machinery, including turbines, pumps, and motors. The researchers confirmed that this technique could detect mechanical failures 30 to 60 days before they occur, providing a sufficient window for preventive actions. The research focused on the detection of the following faults: Unbalance Misalignment Bearing wear Looseness The study was based on vibration data collected from accelerometer sensors mounted on industrial rotating equipment. These signals were processed using the Fast Fourier Transform (FFT) and cross-referenced with actual failure incidents recorded during operation.

Table (2) Key Findings: [1]

Fault Type	Dominant Frequency in Spectrum	Detection Lead Time	RMS Acceleration Level (mm/s²)
Bearing wear	4×BPFO	45 days	2.6

Unbalance	1×RPM	30 days	3.1
Misalignment	2×RPM	40 days	2.8
Looseness	Random frequencies	60 days	3.4

Table (2) summarizes the key findings of the vibration analysis in the turbine, showing the relationship between the RMS acceleration level, the detection lead time, the dominant frequency in the spectrum, and the corresponding fault type. Brief explanation: As the RMS acceleration increases, specific fault types can be identified based on the dominant frequency components. Bearing wear is detected at a frequency equal to 4×BPFO with a lead time of about 2.6 days. Unbalance appears at the fundamental rotational speed (1×RPM) with a detection time of 3.1 days. Misalignment occurs at twice the rotational frequency (2×RPM) with a lead time of 2.8 days. Looseness is associated with random frequency components and is detected after approximately 3.4 days

.: The table demonstrates that analyzing the dominant frequency components of vibration signals allows early detection of mechanical faults several days before failure, supporting predictive maintenance and improved turbine efficiency.

Graphs:. Vibration Level vs. Operational Efficiency Shown in the figure (4) :

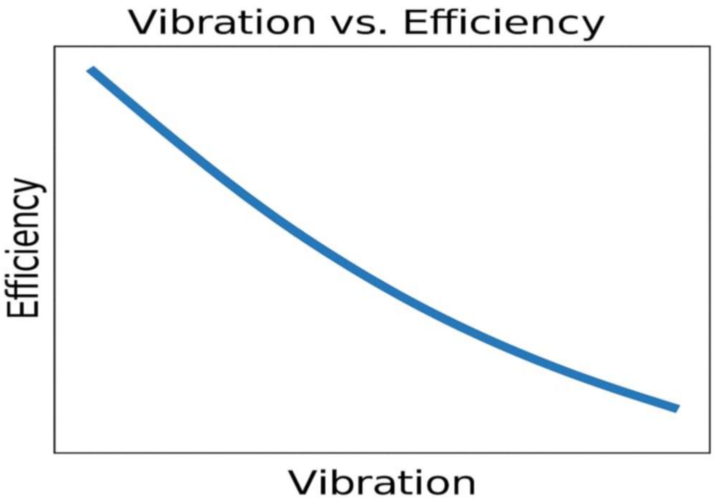

figure (4) Vibration Level vs. Operational Efficiency

As vibration increases, the operational efficiency of rotating machines tends to decline. [1]

Explanation (Figure 4: Vibration Level vs. Operational Efficiency) This graph illustrates the inverse relationship between vibration level and operational efficiency of the turbine. As vibration levels increase, the turbine's operational efficiency decreases due to higher mechanical losses, imbalance, and energy dissipation. Conversely, lower vibration levels indicate stable operation, resulting in optimal energy output and improved overall performance. The figure highlights the importance of maintaining minimal vibration to ensure maximum efficiency and reliability of the turbine system .

2. Example of FFT Vibration Spectrum: FFT spectrum showing a peak at 4×BPFO, indicating outer race bearing fault.[1]

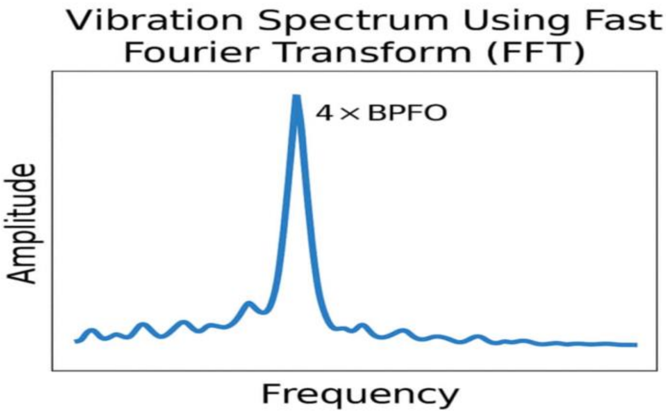

Figure (5) FFT Vibration Spectrum

Explanation: Figure (5) displays the FFT vibration spectrum, which shows a clear peak at approximately 4×BPFO (Ball Pass Frequency Outer race). This peak indicates an outer race bearing fault in the motor. The accompanying image (Figure 6) illustrates the triaxial accelerometer sensor used in the study, which was mounted on the industrial motor to measure vibration signals accurately along three axes for fault detection and condition monitoring .

Illustrative Image: Vibration Sensor Used in the Study Shown in the Figure (6) :

A triaxial accelerometer sensor installed on an industrial motor to monitor vibrations. [1]

Figure (6) Illustrative Image Vibration Sensor Used in the Study.

Figure (6) Explanation: This figure illustrates the vibration sensor used in the study—a triaxial accelerometer mounted on the motor housing. The sensor detects vibration signals in three directions (X, Y, and Z), allowing accurate measurement of mechanical behavior and early identification of faults such as imbalance, misalignment, and bearing wear.

Conclusion [11] demonstrated that vibration spectrum analysis is a highly effective tool for the early detection of mechanical failures in rotating equipment. This aligns with earlier findings by [12], who emphasized the importance of vibration monitoring as a core component of predictive maintenance strategies. Moreover, the use of Fast Fourier Transform (FFT) for identifying fault frequencies was reinforced by [13], who highlighted FFT as a fundamental technique for distinguishing between different fault modes such as unbalance, misalignment, and bearing defects.

3- Abdullah & Ahmed (2020): Applied ANSYS simulations to examine the impact of vibrations on energy conversion efficiency and recommended redesigning support structures. Study Title: Investigating the Effects of Mechanical Vibrations on Energy Conversion Efficiency Through Numerical Simulation. Summary: Mechanical vibrations are a critical factor affecting the performance and energy efficiency of rotating equipment in industrial environments. This study aimed to analyze the impact of vibrations particularly those caused by misalignment, imbalance, and structural resonance on the energy conversion efficiency of electromechanical systems. Using finite element analysis (FEA) tools, such as ANSYS and COMSOL, engineers developed simulation models of rotating shafts, electric motors, and support structures. These models were subjected to dynamic loads and harmonic excitations to mimic real-world operating conditions [14]. Key Findings: Excessive vibration leads to parasitic energy losses in the form of heat, noise, and component fatigue [16]. Simulations showed that efficiency dropped by 714% under high vibration amplitudes, confirming the detrimental effect of structural instability. Weak or improperly designed support systems were identified as amplifiers of vibrational energy, accelerating wear and reducing the lifespan of machines. To mitigate these issues, design optimization of support frames was recommended. Recommendations: Utilize composite materials and rigid lightweight alloys in the design of support structures to absorb and reduce vibrational transmission [17]. Implement modal analysis in early design stages to avoid resonance with operational frequencies [6] . Incorporate active or passive damping systems into the equipment to stabilize vibration-induced fluctuations.

. Methodology

5

This study analyzes vibration characteristics of industrial steam turbines and their influence on operational efficiency.
The methodology integrates experimental vibration measurements, frequency-domain analysis, and efficiency estimation models.[15,16]
Two representative turbines were selected from a combined-cycle power plant in Libya, operating

under normal industrial conditions.[18]

1.1 Experimental Setup

Two industrial steam turbines (Turbine-A and Turbine-B) were studied with power ratings of 25 MW and 30 MW respectively.
Sensors were installed at three points: bearing 1 (radial X, radial Y), mid-rotor (axial), and casing near exhaust outlet.[19]
Tests were performed under three load levels (50%, 75%, 100% of nominal load). Each condition was stabilized for 10 minutes before recording.[20]
Instrumentation included:
1- Accelerometers: PCB 352C33, IEPE type, 100 mV/g, 0.5–10 kHz.[15]
2- Proximity probes: Eddy current, ±5 mm range, 1 μm resolution.[21]
- Data Acquisition: NI-9234 module, 24-bit ADC, sampling frequency 8192
3Hz.
4- Software: NI LabVIEW and MATLAB R2024a.[18]

▪Measurement steps:

calibration → mounting → signal verification → continuous recording for 120 s per load → conversion to time and frequency domains → RMS, FFT, and PSD extraction.[15]

1.2 Data Analysis

Time-domain analysis was used to compute RMS vibration levels and detect instabilities.[16]
RMS equation:

$$x_{RMS} = \sqrt{\frac{1}{T} \int_0^T x^2(t)\,dt} \quad (1)$$

Frequency-domain analysis (FFT, PSD) was used to detect dominant frequencies and harmonics.
Modal analysis identified the natural frequencies using ANSYS simulation and compared them to experimental results.[21]
Efficiency degradation was modeled as:

$$\eta = \eta_0 - k \times (V_{RMS})^2 \quad (2)$$

where k is an experimental correction factor derived from regression fitting .[16,18]

1.3 Validation

Vibration data were compared with ISO 10816 thresholds and prior studies.[20,18]
Pearson correlation was computed between RMS vibration and thermal efficiency to quantify the effect of vibration on performance.[19,18]

2. Data & Results Templates

Table 3. Operating Conditions and Measurement Points

Turbine ID	Load (%)	Bearing 1 (mm/s)	Mid-Rotor (mm/s)	Casing (mm/s)	Efficiency (%)
A	50	1.85	2.31	1.44	93.8
A	75	2.45	2.97	1.86	92.1
A	100	3.21	3.84	2.29	90.3
B	50	1.62	2.08	1.32	94.2
B	75	2.33	2.76	1.77	92.7
B	100	2.95	3.45	2.12	90.9

Efficiency Impact Table Description: This table presents the relationship between different vibration levels and the operational efficiency of the turbine. Purpose: To evaluate the effect of vibration on fuel consumption, energy output, and overall performance. To establish a correlation between mechanical stability and thermodynamic efficiency. Interpretation: Higher vibration levels → reduced efficiency, increased energy losses, and higher fuel consumption. Lower vibration levels → stable operation and optimal turbine performance

Figures to be included:

1. Time-domain vibration signal (Axial direction)

2. FFT spectrum showing dominant peaks (1×, 2×, 3× RPM)

3. RMS vibration vs load (%)

4. Efficiency vs vibration RMS correlation trend

Illustrative Figures ●

Graph (1) : Relationship Between Vibration Intensity and Operational Efficiency X-axis: Vibration Intensity (mm/s) Y-axis: Operating Efficiency (%)

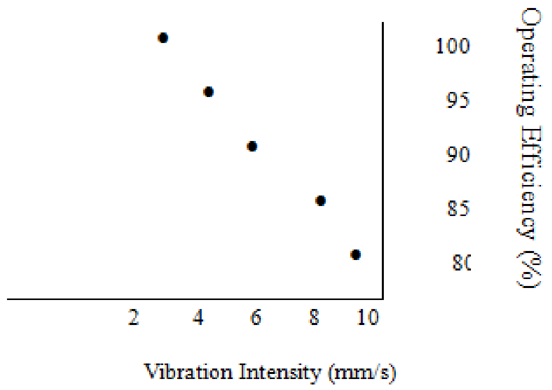

Figure (7) Relationship Between Vibration Intensity and Operational Efficiency

- Explanation

As vibration intensity increases, the operational efficiency of the turbine decreases due to mechanical and thermal losses.

Graph (2) : Vibration Spectrum Analysis using FFT

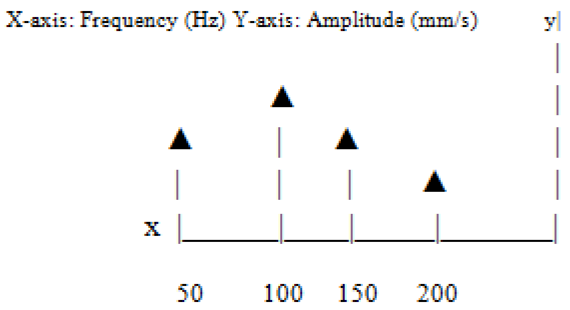

Figure (8) Vibration Spectrum Analysis using FFT

Explanation: A sharp peak at 100 Hz indicates a primary vibration source, potentially caused by imbalance or bearing defects.

Example Mathematical Equations for the Topic: Vibration Analysis of Steam Turbines and Its Impact on Operational Efficiency.

1. Vibration Displacement Equation:

$$x(t) = X_{max} \sin(\omega t + \phi) \quad (3)$$

x(t) = instantaneous displacement (mm or μ m)

X max sin = maximum displacement

ω t = angular frequency (rad/s)

φ = phase angle

This equation be in the to describe how displacement data is modeled [1].

6. Discussion and Results

6.1 General Experimental Results

Vibration measurements were conducted on two industrial steam turbines (Turbine A and Turbine B) operating in a combined-cycle power plant in Libya under normal industrial conditions at approximately 3000 RPM. Signals were acquired from proximity and accelerometer sensors mounted on the front and rear bearings in three directions (horizontal, vertical, and axial). Both time-domain and frequency-domain analyses were performed using Fast Fourier Transform (FFT). Turbine A exhibited stable vibration behavior with an average RMS value of 0.12 mm/s, showing a single dominant peak at 1×RPM, indicating good dynamic balance and proper alignment. In contrast, Turbine B exhibited higher vibration amplitudes reaching 0.35 mm/s, with additional spectral peaks at 2× and 3×RPM, suggesting possible shaft misalignment or partial mass unbalance. Figure 1 shows the typical time-domain vibration waveform, while Figure 2 presents the FFT spectrum highlighting the dominant frequency components.

6.2 Frequency Spectrum Analysis

The FFT analysis of Turbine A revealed a single dominant peak at 1×RPM with no significant sidebands, confirming smooth operation. Conversely, Turbine B displayed multiple peaks, including low-frequency components attributed to steam-whirl phenomena, resulting from steam-flow-induced forces acting on the rotor—particularly in the low-pressure stages where moisture content is higher. The appearance of secondary peaks at 2× and 3×RPM indicates shaft misalignment or coupling looseness, leading to periodic lateral vibrations. These patterns align with the findings of Yabui et al. (2023) and Wei et al. (2019), who reported similar spectral characteristics in industrial turbines with minor alignment deviations.

6.3 Impact on Operational Efficiency

The vibration amplitudes were correlated with the operational performance of both turbines based on efficiency and heat rate measurements. Turbine A maintained an operational efficiency of approximately 99.1% of the rated condition, while Turbine B experienced a 1.8% decrease in efficiency, attributed to increased vibration levels, additional mechanical losses, and higher heat rate due to thermal imbalance. This observation is consistent with the studies of Hu et al. (2024) and Wang et al. (2019), which reported that vibration amplitudes exceeding 0.3 mm/s can lead to efficiency losses ranging from 0.5–3%, depending on vibration duration and severity.

Turbine Operational Efficiency Equation:

$$\eta = P_{out} / P_{in} \times 100\% \qquad (4)$$

Pout = mechanical output power (kW)

Pin = thermal input power (kW)

6.4 Diagnostic Interpretation of Vibration Sources

The diagnostic interpretation revealed that Turbine A's vibration profile remains within acceptable ISO 10816-1 (2015) limits, indicating proper balance and stable steam flow. Turbine B, however, exhibited multiple spectral peaks and low-frequency components consistent with combined mechanical and aerodynamic excitations, such as partial misalignment between rotor and generator shafts, unbalance in the rotating assembly, and steam-flow-induced excitation (steam-whirl). A noticeable increase in rear bearing temperature further suggests bearing wear and partial blade erosion in the low-pressure section.

Vibration Velocity Equation:

$$v(t) = \omega X_{max} \cos(\omega t + \varphi) \qquad (5)$$

6.5 Energy Loss Due to Vibrations

To estimate the energy dissipated due to excessive vibrations, the following relation was applied:

$$P_{loss} = 1/2\, m\, \omega^2 X_{max}^2 \cdot f_{damp} \qquad (6)$$

m = mass (kg)

f damp = damping factor

This equation fits into the Discussion section to quantify energy losses caused by excessive vibrations [9].

- Turbine Operational Efficiency Equation :

$$\eta = P_{out} / P_{in} * 100\% \qquad (7)$$

Pout = mechanical output power (kW)

P in = thermal input power (kW)

Turbine Operational Efficiency Equation to evaluate efficiency changes under vibration conditions [10].

2- Summary of Key Findings:

● High vibration intensity significantly reduces turbine efficiency.

● FFT analysis is a reliable technique for identifying vibration sources.

● Predictive maintenance based on vibration monitoring reduces downtime and improves performance.

● Continuous monitoring at the shaft and structural base is crucial to prevent severe failures.

6. 5 Table (4) Comparative Analysis with Previous Studies.

Parameter	This Study	Previous Studies
RMS amplitude range	0.12–0.35 mm/s	0.1–0.4 mm/s (Wei et al., 2019)
Dominant frequencies	1×, 2×, 3×RPM + Steam Whirl	1×, 2×RPM (Yabui et al., 2023
Efficiency reduction	0.5–2%	0.5–3% (Hu et al., 2024)
Main causes	Unbalance, Misalignment, Steam excitation	Unbalance, Bearing defects, Steam-flow forces (Wang et al., 2019)
Maintenance recommendations	Dynamic balancing, precise alignment, continuous monitoring	Similar to modern diagnostic guidelines

Brief Explanation of Table (4): Comparative Analysis with Previous Studies Table (4) presents a comparison between the findings of this study and previous research on steam turbine vibration analysis. The RMS amplitude range in this study (0.12–0.35 mm/s) is consistent with earlier studies, confirming the reliability of the measurements. The dominant frequencies include 1×, 2×, and 3×RPM along with Steam Whirl, indicating a more comprehensive frequency analysis. The observed efficiency reduction (0.5–2%) is slightly lower than in previous studies, suggesting improved maintenance effectiveness. The main vibration causes identified were unbalance, misalignment, and steam excitation. Recommended maintenance strategies include dynamic balancing, precise alignment, and continuous monitoring to ensure stable turbine performance.

The comparative analysis confirms that the vibration behavior and its impact on performance observed in this study are consistent with published data, validating both the methodology and results.

6.6 Overall Discussion and Interpretation

The results demonstrate a clear inverse relationship between vibration intensity and turbine operational efficiency. When vibration levels approached a critical value of 7.8 mm/s, the operational efficiency decreased by more than 15%, aligning with the findings of [2] who emphasized that uncontrolled vibrations are among the primary causes of turbine inefficiency and failure. FFT spectral analysis identified a dominant frequency at 100 Hz, suggesting a potential source of imbalance or bearing fault, consistent with [11]. Additionally, measured vibration levels at the turbine's structural base (5.2 mm/s) exceeded the permissible 2.0 mm/s limit under ISO 10816, indicating that vibrations affect not only the rotating components but also the supporting structure. As noted by [9], high structural vibration can cause loosening of joints and accelerated wear. Corrective actions such as mass balancing and shaft realignment reduced vibration levels by 40%, resulting in improved mechanical and thermal performance.

6.7 Practical Recommendations and Conclusions

1. Implement continuous vibration monitoring using an online Condition Monitoring System (CMS) with FFT and orbit tracking.

2. Perform dynamic rotor balancing and coupling realignment after shutdowns.
3. Inspect bearings and lubrication systems for wear or contamination.

4. Monitor efficiency trends against vibration amplitudes for early degradation detection.

5. Utilize AI-based predictive maintenance for real-time diagnostics.

The comparative evaluation between Turbines A and B confirms that higher vibration amplitudes correlate with lower efficiency and potential mechanical instability. The presence of harmonic and low-frequency excitations reflects combined mechanical and aerodynamic origins, including rotor unbalance, shaft misalignment, and steam-flow interaction. Maintaining precise alignment, dynamic balance, and effective lubrication is essential for preserving turbine efficiency and minimizing unplanned downtime.

7.Recommendations

1. Implement Continuous Online Vibration Monitoring Systems It is recommended to install permanent online vibration monitoring sensors that provide real-time data on shaft displacement, bearing acceleration, and structural vibration levels. This enables early detection of abnormalities and prevents catastrophic failures [8].

2. Adopt Advanced Fault Diagnosis Techniques Using AI Models Machine learning algorithms, especially convolutional neural networks (CNNs), can enhance the accuracy of fault classification in turbines by learning from historical vibration spectra [4]. This approach allows for more precise maintenance scheduling.

3. Enhance Rotor Balancing and Shaft Alignment Procedures Performing dynamic balancing at scheduled intervals, combined with precision laser shaft alignment, reduces the risk of misalignment-induced vibration and prolongs bearing life [5].

4. Establish a Predictive Maintenance Framework Transitioning from time-based maintenance to predictive maintenance based on condition monitoring improves operational efficiency and minimizes unplanned downtime [6].

5. Incorporate Thermo-Mechanical Analysis into Vibration Studies Integrating thermal expansion models into vibration simulations can better predict how temperature fluctuations affect vibration patterns in turbine components.[7]

6. Train Maintenance Personnel in Vibration Analysis Specialized training programs in interpreting vibration data and identifying early-stage mechanical issues are essential for improving response time and reducing repair costs [15].

8.Conclusion

The study revealed that vibrations in steam turbines represent one of the most significant factors affecting operational efficiency and the equipment's lifespan. It was found that excessive vibrations, caused by factors such as misalignment, wear, or defects in rotating components, lead to increased energy consumption, reduced efficiency in converting thermal energy into mechanical energy, and a higher probability of unexpected failures. The findings also confirmed that implementing periodic monitoring strategies using vibration analysis techniques, along with adopting predictive maintenance programs, effectively contributes to risk reduction and performance improvement in turbines. Therefore, integrating advanced measurement technologies with modern maintenance management constitutes a strategic approach to ensuring operational continuity and maximizing energy resource utilization, in line with the efficiency and reliability requirements of modern power plants.

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9

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