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Vibration Analysis as a Transformative Approach to Condition-Based Monitoring

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Abstract
Effective maintenance of industrial machinery is essential for reducing operational downtime, minimizing maintenance costs, and improving equipment reliability. This study investigates vibration analysis as a diagnostic technique for condition-based monitoring (CBM) of rotating machinery. Experimental investigations were conducted on two industrial systems: a centrifugal pump and a CAT V12 diesel engine. Vibration signals were obtained using tri-axial accelerometers installed at key monitoring points and analysed using Fast Fourier Transform (FFT) to identify dominant vibration frequencies associated with mechanical faults. The results from the centrifugal pump showed a progressive increase in vibration amplitude with increasing rotational speed, indicating possible shaft misalignment and rotor imbalance. For the diesel engine, vibration characteristics varied with cooling water temperature due to thermal stress and mechanical loading conditions. The measured vibration levels were evaluated using ISO vibration severity standards. The findings demonstrate that vibration analysis is an effective predictive maintenance tool capable of detecting early mechanical faults in industrial machinery. Integrating vibration monitoring into condition-based maintenance programs can significantly enhance equipment reliability, reduce unexpected failures, and improve operational efficiency in industrial systems.

Keywords: *Centrifugal pump, Condition-based monitoring, Diesel engine, Fast Fourier Transform, Predictive maintenance, Vibration analysis.*

1.0 Introduction

Modern industrial operations increasingly depend on the reliable and continuous performance of rotating machinery including turbines, pumps, compressors, and internal combustion engines. These machines comprise of the core of production systems in sectors including petrochemical processing, power generation, manufacturing, and transportation [1, 2, 3]. Any unexpected failure of such equipment can lead to severe operational interruptions, safety hazards, environmental incidents, and substantial economic losses because of unplanned downtime [4, 5]. Subsequently, maintenance strategies have grown from reactive approaches to advanced predictive maintenance frameworks aimed at improving equipment reliability and operational efficiency [6].

Maintenance management plays a vital role in guaranteeing system reliability, operational sustainability, and cost effectiveness in industrial environments. Historically, industries depend on heavily on reactive maintenance, commonly referred to as the run-to-failure method, where machinery is repaired only after breakdown occurs. Although simple to implement, this approach often results in prolonged equipment downtime, increased spare-part consumption, and reduced machinery lifespan [7, 8]. To overwhelmed these limitations, preventive maintenance approaches were introduced, where maintenance activities are performed at predetermined time intervals regardless of equipment condition [9, 10]. Despite the fact, preventive maintenance reduces the likelihood of sudden failures, it frequently leads to needless component replacement and increased maintenance costs because of the lack of real-time machine condition assessment [4].

In recent years, Condition-Based Monitoring (CBM) has appeared as a more effective maintenance approach that focuses on monitoring the real-time health condition of machinery using measurable operational parameters such as vibration, temperature, acoustic emissions, and lubricant characteristics [2, 6, 11]. According to Sharma et al. [3], contrasting preventive maintenance, CBM permits maintenance actions to be scheduled based on the actual operating condition of equipment rather than fixed time intervals. This approach significantly enhances maintenance efficiency by enabling early fault detection and reducing unnecessary servicing operations [12].

Amid the various CBM techniques, vibration analysis has become one of the most widely used diagnostic tools for monitoring rotating machinery [13, 14]. Every mechanical system generates characteristic vibration signatures during operation due to dynamic forces acting on its components [15]. Deviations from normal vibration patterns often specify the presence of mechanical faults including imbalance, shaft misalignment, bearing defects, looseness, or gear wear [16, 17, 18]. Park et al. [19] reported that the means of analyzing these vibration signals, engineers can detect anomalies at an early stage and implement corrective actions before catastrophic failures occur.

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An important technique used in vibration diagnostics is the Fast Fourier Transform (FFT)**,** which converts vibration signals from the time domain to the frequency domain, enabling the identification of dominant frequencies associated with specific mechanical faults [14, 15]. Chen et al. [20] stated that frequency-based analysis is particularly useful in diagnosing problems in rotating machinery because many faults generate unique spectral signatures that correspond to shaft rotational frequencies or their harmonics. Thus, FFT-based vibration analysis has become a vital tool in predictive maintenance programs for industrial equipment [21].

In spite of the proven advantages of CBM, many industries predominantly in developing economies still face challenges in implementing predictive maintenance systems due to limited technical expertise, inadequate monitoring infrastructure, and insufficient data analytics capabilities [10, 22]. As a result, mechanical faults such as shaft misalignment, bearing degradation, and rotor imbalance often remain undetected until severe damage occurs, leading to costly equipment failures and production losses [23].

Vibration analysis provides a transformative pathway toward improving predictive maintenance by enabling continuous monitoring and early fault detection in rotating machinery. Through systematic acquisition and analysis of vibration signals, it becomes possible to diagnose mechanical anomalies, understand machine behavior under different operating conditions, and predict potential failures before they occur [24, 25]. Though, the effectiveness of vibration-based condition monitoring depends on accurate data acquisition, proper signal processing techniques, and correct interpretation of vibration spectra [13].

Therefore, this study investigates vibration analysis as a predictive tool for condition-based monitoring of industrial machinery. Experimental investigations were conducted on two representative industrial systems: a centrifugal pump and a CAT V12 diesel engine. The study evaluates vibration characteristics under varying operational conditions including rotational speed and cooling water temperature. Fast Fourier Transform (FFT) analysis was applied to identify vibration patterns and potential fault indicators. The findings aim to demonstrate the effectiveness of vibration monitoring in improving predictive maintenance strategies, enhancing equipment reliability, and reducing operational downtime in industrial systems.

2.0 Materials and Methods/Methodology

2.1 Study Area and Equipment Specifications

The experimental investigation was conducted at Heritage Energy Operational Services Limited, where industrial rotating equipment are routinely monitored for maintenance diagnostics. Two representative rotating machines were selected for the study:

1. Centrifugal pump (NOV SB8×6–14 model)
2. CAT V12 diesel engine (Model G3512C)

These machines were selected because centrifugal pumps and diesel engines represent critical equipment widely used in oil and gas, manufacturing, and power generation industries. The centrifugal pump has a rated capacity of 320 m^3/h, head of 40 m, and motor power of 73 kW, while the CAT V12 diesel engine is a four-stroke engine with a maximum power output of 1500 HP and a compression ratio of 13:1.

These machines were instrumented with tri-axial piezoelectric accelerometers mounted at strategic monitoring points to capture vibration signals along the axial, radial, and tangential directions. Monitoring points included motor drive end (DE), motor non-drive end (NDE), pump drive end, pump non-drive end, and engine mounting frame. These locations were selected based on standard vibration monitoring practices recommended for rotating machinery diagnostics [15, 26]. The specifications of the studied equipment were shown in Tables 1 and 2.

Table 1: Centrifugal Pump Specification

Parameter	Units	Specification
Make	-	NOV (National Oilwell Varco)
Model	-	SB8x6-14
Capacity	m^3/h	320
Head	m	40
Efficiency	%	65
Net positive suction head (NPSH)	m	4.0
Shaft power	kW	53.63
Motor power	kW	73

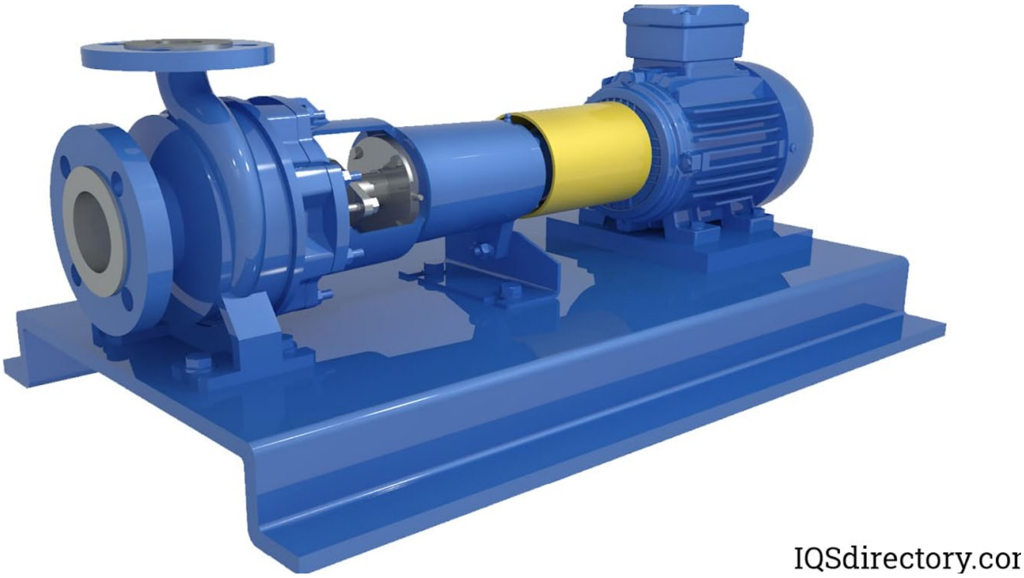

Figure 1: Centrifugal pump used for the vibration monitoring experiment (NOV SB8×6–14 model)
Source: Adapted from NOV Inc. [27] product catalogue

Table 2: CAT V12 Diesel Engine Specification

Parameter	Units	Specification
Make	-	Caterpillar
Model	-	G3512C
Engine Configuration	-	V12 Four stroke cycle
Maximum power	HP	1500
Maximum torque	rpm	1400
Compressor ratio	-	13.0:1

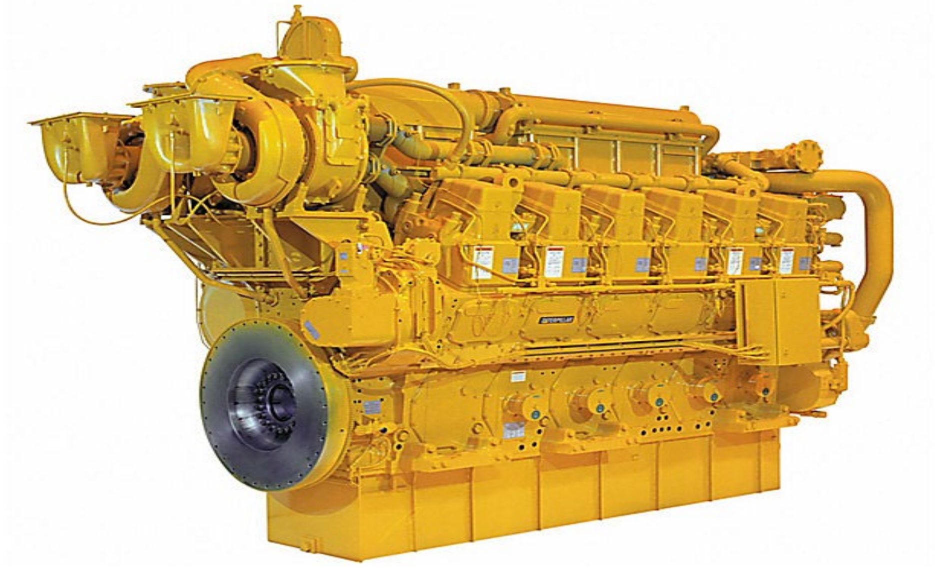

Figure 2: CAT V12 diesel engine (Model G3512C) used for vibration analysis
Source: Adapted from Caterpillar Inc. [28] technical specifications manual

2.2 Vibration Measurement System

To measure machine vibration, tri-axial piezoelectric accelerometers were mounted at critical monitoring locations on the rotating machinery. These sensors were connected to a portable vibration analyzer capable of performing Fast Fourier Transform (FFT) analysis. The accelerometers were installed at standard diagnostic positions including motor drive end (DE), motor non-drive end (NDE), pump drive end, and pump non-drive end. The sensor mounting locations and vibration monitoring points on the centrifugal pump are illustrated in Figure 3.

Similarly, accelerometers were installed on the diesel engine at selected structural locations to capture vibration signals generated during engine operation. These monitoring points were selected based on standard vibration

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diagnostic practices for internal combustion engines. The accelerometer installation points on the diesel engine are presented in Figure 4.

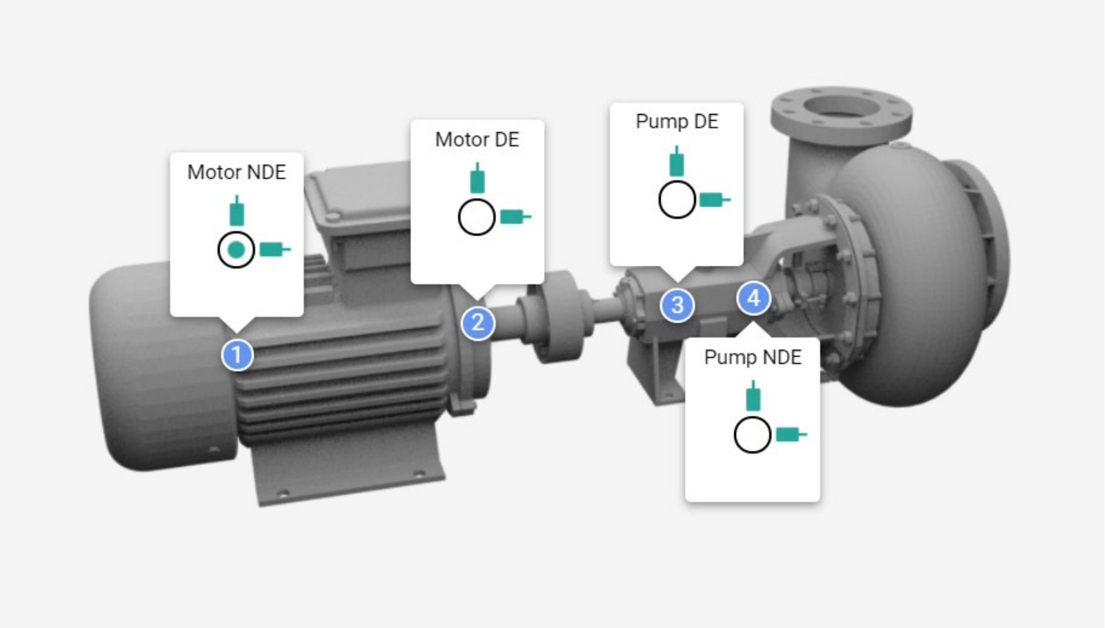

Figure 3: Accelerometer mounting locations and vibration monitoring points on the centrifugal pump.
Source: Modified from Randall [15]

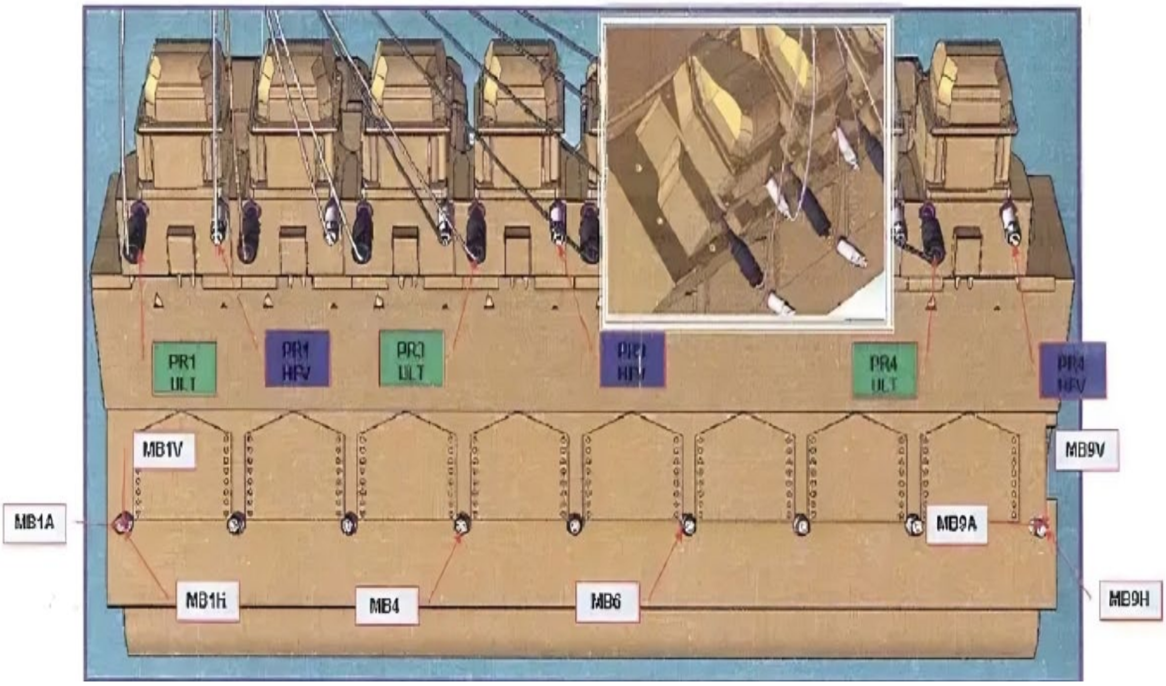

Figure 4: Accelerometer installation points on the CAT V12 diesel engine for vibration monitoring
Source: Adapted from Mobley [8]

2.3 Experimental Procedure

2.3.1 Centrifugal Pump Test

The centrifugal pump was operated at different rotational speeds ranging from **25 Hz to 50 Hz.** Vibration velocity measurements were recorded at each speed level after the machine reached stable operating conditions.

2.2.2 Diesel Engine Test

For the diesel engine experiment, vibration measurements were recorded at cooling water temperatures between 25 °C and 45 °C. The following vibration parameters were measured: RMS acceleration, RMS velocity,

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RMS displacement, and Noise level. These parameters provided a comprehensive assessment of engine vibration behaviour under varying thermal conditions.

2.4 Data Processing and Analysis

The recorded vibration signals were processed using Fast Fourier Transform (FFT**)** to convert the signals from the time domain into the frequency domain. This allowed identification of dominant vibration frequencies associated with mechanical faults. The measured vibration levels were evaluated using ISO vibration severity standards (ISO 10816) [27], which classify machine vibration into different condition zones based on vibration velocity levels.

Table 3: ISO Vibration Severity Standards

Zone	Vibration Level (mm/s)	Machine Condition
Zone A	0 – 1.8	Good condition
Zone B	1.8 – 2.8	Acceptable condition
Zone C	2.8 – 4.5	Unsatisfactory condition
Zone D	>4.5	Unacceptable condition

Machines operating in Zone A or B are considered to be in satisfactory condition, while machines in Zone C require corrective maintenance. Machines in Zone D require immediate shutdown and repair [2]. In this study, the measured vibration levels were compared with these ISO thresholds to determine the mechanical health of the tested equipment.

Materials, methods and equipment used for the work should be expressly described in this section. All prescribed formatting styles must be followed, to avoid delay in processing of the manuscript.

3.0 Results and Discussion

3.1 Centrifugal Pump Vibration Analysis

The vibration amplitude measurements obtained from the centrifugal pump and motor indicate a progressive increase in vibration levels with increasing rotational speed. As presented in Table 4, the motor vibration amplitude increased from **0.393 mm/s at 25 Hz to 2.91 mm/s at 50 Hz**, while the pump vibration amplitude increased from **0.50 mm/s to 3.07 mm/s** across the same operating speed range. The corresponding vibration trends are illustrated in **Figures 5 and 6.**

This observed increase in vibration amplitude with rotational speed is consistent with rotor dynamic theory, which indicates that centrifugal forces acting on rotating components increase proportionally with rotational speed, resulting in higher vibration amplitudes [8, 15]. At lower rotational speeds between **25 Hz and 40 Hz**, the measured vibration amplitudes remained within **ISO Zone A and Zone B**, which correspond to good and acceptable operating conditions according to ISO vibration severity standards. However, at **50 Hz**, the vibration amplitudes exceeded **2.8 mm/s**, placing the machine within **ISO Zone C**, which indicates an unsatisfactory operating condition requiring corrective maintenance [26]. Elevated vibration levels in centrifugal pumps are often associated with mechanical faults such as rotor imbalance, shaft misalignment, looseness, or bearing wear [14, 20]. Rotor imbalance typically occurs when the mass distribution of the rotating element is uneven, causing periodic centrifugal forces that generate vibration at the shaft rotational frequency [13]. Similarly, shaft misalignment between the pump shaft and motor shaft can produce harmonic vibration components that increase with rotational speed [21]. Previous studies have reported similar vibration patterns in centrifugal pumps operating under misaligned or unbalanced conditions [19, 23]. The vibration trend observed in this study is therefore consistent with findings reported in earlier research on vibration-based fault diagnosis of centrifugal pumps [14, 20]. The results demonstrate that vibration monitoring provides an effective method for detecting mechanical anomalies in rotating machinery before severe damage occurs.

Table 4: Result of Vibration Amplitude Measurement of Pump and Motor

Vibration Amplitude (Hz)	Motor Speed (mm/s)	Pump Speed (mm/s)
25	0.393	0.50
30	0.602	0.56
35	0.646	0.594
40	0.815	0.646
45	1.1	1.06
50	2.91	3.07

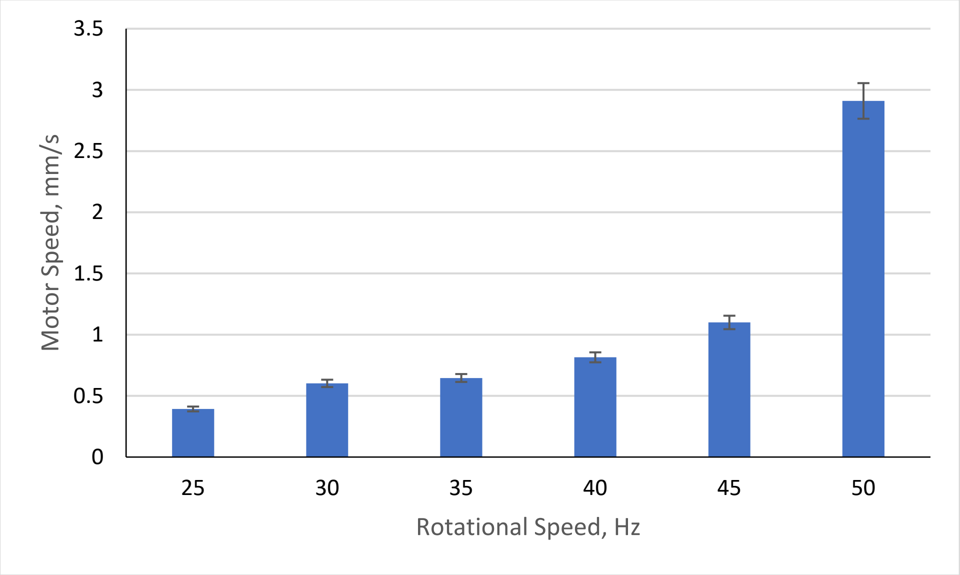

Figure 5: Motor Vibration Trend with Increasing Rotational Speed

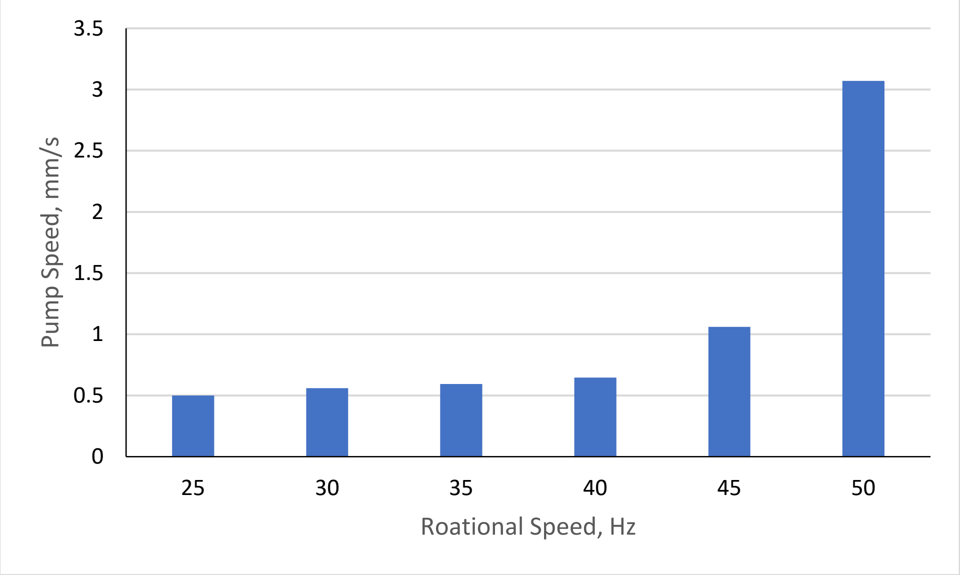

Figure 6: Pump Vibration Trend with Increasing Rotational Speed

3.2 Diesel Engine Vibration Analysis

The vibration behaviour of the CAT V12 diesel engine was analyzed under varying cooling water temperature conditions. The RMS displacement values presented in Table 5 indicate that vibration amplitude increased from **152 µm at 25 °C to 169 µm at 35 °C**, suggesting that increasing thermal loading influences engine vibration behaviour. However, beyond **35 °C**, the vibration amplitude decreased slightly, reaching **164 µm at 45 °C**.

Thermal effects play a significant role in influencing vibration characteristics of internal combustion engines. As engine temperature increases, thermal expansion of engine components such as pistons, cylinder liners, and crankshafts may alter mechanical clearances and dynamic loading conditions [16]. Increased combustion pressure and mechanical loading may also contribute to higher vibration amplitudes during engine operation [11].

The increase in vibration amplitude observed between **25 °C and 35 °C** can therefore be attributed to thermal stress and increased combustion-induced excitation forces within the engine structure. Similar observations were reported by **Rahman et al. [16]**, who found that vibration intensity in diesel engines increased with temperature due to thermal expansion and combustion dynamics. However, the slight reduction in vibration amplitude observed beyond **35 °C** may indicate stabilization of thermal stresses and improved lubrication performance within the engine components. Engine lubrication properties are known to improve with moderate temperature increases, which can reduce friction-induced vibrations [3]. These findings are consistent with previous research on vibration monitoring of internal combustion engines, which shows that temperature variations significantly influence engine vibration behaviour and diagnostic signals [18, 25].

Table 5: RMS Values for Different Temperatures

S/N	**Cooling Water Temperature (°C)**	**RMS Acceleration (mm/s^2)**	**RMS Velocity (mm/s)**	**RMS Displacement** (μm)	**RMS Noise (Pa)**
1	25	24.5	29.7	152	3.28
2	30	24.4	30.7	167	3.45
3	35	23.8	30.9	169	3.35
4	40	23.5	30.9	167	3.38
5	45	22.8	29.9	164	3.22

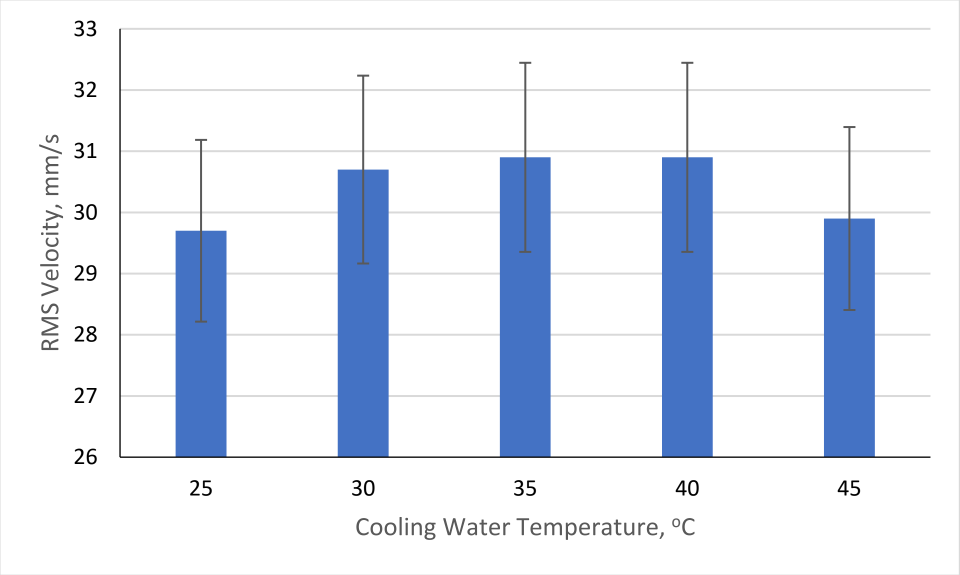

Figure 7: Effect of Cooling Water Temperature on RMS Velocity

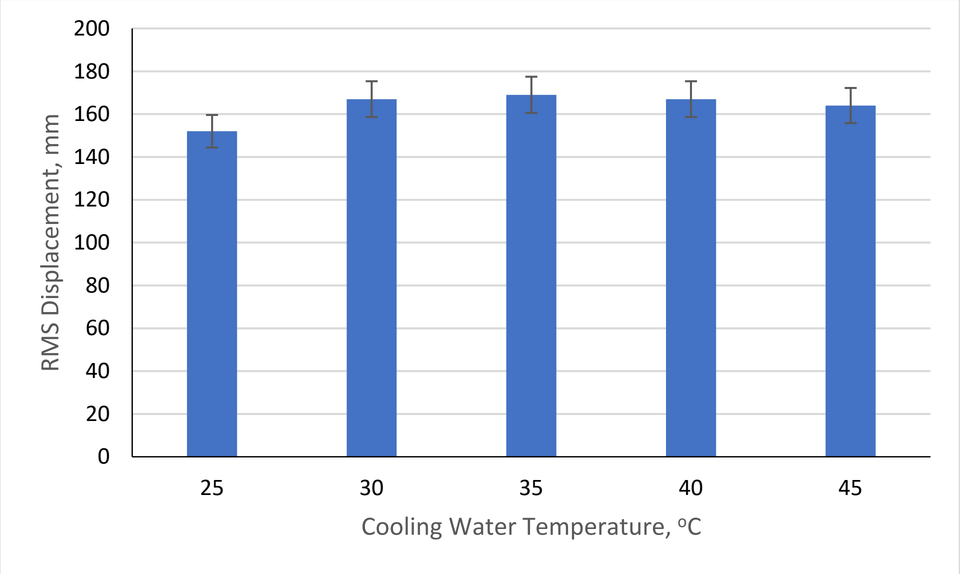

Figure 8: Effect of Cooling Water Temperature on RMS Displacement

3.3 Implications for Predictive Maintenance

The results obtained from both the centrifugal pump and diesel engine experiments highlight the importance of vibration monitoring as a predictive maintenance tool for industrial rotating machinery. Increasing vibration amplitude with operating speed or temperature can serve as an early indicator of mechanical faults such as imbalance, misalignment, or component wear.

By implementing continuous vibration monitoring systems, maintenance engineers can detect abnormal machine behaviour at an early stage and implement corrective maintenance before catastrophic equipment failure occurs [5, 6]. Condition-based maintenance strategies supported by vibration monitoring have been shown to significantly reduce maintenance costs and equipment downtime in industrial environments [1].

Furthermore, recent advances in machine learning and data-driven predictive maintenance have enabled automated detection of vibration anomalies using large datasets obtained from industrial monitoring systems [10, 23]. Integrating vibration monitoring with artificial intelligence techniques can therefore further enhance fault diagnosis accuracy and predictive maintenance performance.

Overall, the findings of this study confirm that vibration analysis remains one of the most reliable diagnostic tools for monitoring the health condition of rotating machinery and improving maintenance decision-making in industrial systems.

4.0 Conclusion

This study investigated vibration analysis as a diagnostic approach for condition-based monitoring of rotating machinery. Experimental investigations conducted on a centrifugal pump and a CAT V12 diesel engine showed that vibration characteristics vary significantly with operating conditions such as rotational speed and temperature. The application of Fast Fourier Transform analysis enabled identification of vibration patterns associated with mechanical faults including rotor imbalance and shaft misalignment. The results demonstrate that vibration monitoring provides valuable information for predictive maintenance and early fault detection in industrial machinery.

Integrating vibration analysis into condition-based maintenance programs can improve equipment reliability, reduce maintenance costs, and minimize unexpected operational downtime. Future research may focus on integrating machine learning algorithms with vibration monitoring systems to enhance automated fault detection and predictive maintenance capabilities.

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