Pertanika J. Sci. & Technol. 33 (2): 725 - 744 (2025)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Effective Vibration-Based Anomaly Detection in Water Pump Operation Using Arduino Microcontroller

Azahar Mohd[1], Khairil Anas Md Rezali[1]*, Sharafiz Abdul Rahim[1], Mohammad Yazdi Harmin[2], Abdul Murad Zainal Abidin[3] and Mohamad Fikri Mohamad Yunus[3]

[1]*Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia*

[2]*Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia*

[3]*Mechanical Research Laboratory, Centre of Excellence for Engineering and Technology (CREaTE), Public Works Department Malaysia, 78000 Alor Gajah, Melaka, Malaysia*

ABSTRACT

Arduino microcontroller and ADXL accelerometer are commonly paired devices, often considered for creating inexpensive vibration analysers. Many researchers have proven that both pairing devices have good performance in vibration measurement and have the potential for commercialisation. This study evaluates the feasibility of vibration measurement and monitoring using an Arduino microcontroller with an inexpensive accelerometer in detecting anomalies during water pump operation. A dedicated Arduino Mega and an ADXL345 accelerometer were attached to a water pump motor to facilitate continuous monitoring of vibrations. The vibration measurement was set at a sampling rate of 530 Hz. Vibration data in RMS value was sent to the cloud storage for monitoring. Raw data captured during normal and abnormal conditions were collected at the site when anomalies were detected for further analysis. The results showed that the abnormal conditions could be clearly differentiated from normal conditions using the Fast Fourier Transform method and spectrogram analysis. In summary, this study confirms that integrating the Arduino Microcontroller with the ADXL accelerometer effectively detects irregularities in the operating conditions of the water pump.

Keywords: ADXL accelerometer, Arduino microcontroller, vibration monitoring, water pump anomalies

ARTICLE INFO

Article history:
Received: 29 May 2024
Accepted: 04 November 2024
Published: 21 February 2025

DOI: https://doi.org/10.47836/pjst.33.2.09

E-mail addresses:
gs67345@student.upm.edu.my (Azahar Mohd)
khairilanas@upm.edu.my (Khairil Anas Md Rezali)
sharafiz@upm.edu.my (Sharafiz Abdul Rahim)
myazdi@upm.edu.my (Mohammad Yazdi Harmin)
abdmurad@jkr.gov.my (Abdul Murad Zainal Abidin)
mfikri@jkr.gov.my (Mohamad Fikri Mohamad Yunus)
* Corresponding author

ISSN: 0128-7680
e-ISSN: 2231-8526

INTRODUCTION

Arduino Microcontroller is a popular platform in the field of electronic development, providing a microcontroller system that is easy to program and interact with various electronic devices (Kondaveeti et al., 2021; Pan & Zhu, 2018). One of the frequently used models is the Arduino Mega 2560, which offers a wide range of capabilities to control external sensors and devices, making it the primary choice for measurement and monitoring in a variety of environments. The importance and suitability of the water pump system in daily life make it suitable for applying this technology. Together with Arduino microcontrollers, accelerometers are often used as sensors to measure acceleration and position changes in three axes. The ADXL345 accelerometer, used as a sensor in this study, is notable for its compact size, lightweight design, user-friendliness, and high precision (Adli & Rusmin, 2020). These sensors enable vibration measurement in a variety of applications, including machine health monitoring and structural damage detection. In the context of water pumps, the use of this combination enables accurate and rapid monitoring of the operating conditions of water pumps, helping to avoid unwanted damage and ensuring the smoothness of the water supply for daily needs (ALTobi et al., 2019).

The cold-water supply system in a building is a system of basic needs that is very important and must be provided especially to ensure the quality of life and the health of the population is guaranteed. As living standards rise, there is a growing demand for improved comfort, quality, and safety at affordable prices (Lourenço et al., 2022). Water supply systems in buildings must keep pace with this trend to meet the demand for clean drinking water (Van Der Schee, 2009). For high-rise buildings, water distribution often relies on pumping systems due to the structure's height or inadequate water pressure from the source (Midiani et al., 2023; Altherr et al., 2019). In such scenarios, ensuring the continuous upkeep of the pump system is imperative to avoid disruptions in the water supply for the building's occupants (Kiliç et al., 2017). The malfunction of a water pump system causes inconvenience for users and substantially impacts maintenance expenses (Zhou et al., 2021; Dutta et al., 2020). Therefore, it is crucial to regularly maintain the system to extend its longevity and preserve its effectiveness (Dutta et al., 2020). Nevertheless, routine maintenance is insufficient, as pump faults or anomalies during operation can arise unexpectedly without immediate detection.

Anomalies in the water pump system can be caused by several factors, such as wear and tear, ageing components, bearing failure, shaft misalignment, and excessive physical stress (Chen et al., 2022; Shibnauth & Surnam, 2015; Yehl et al., 2008). Although these factors can be identified through physical examination, certain issues, such as cavitation and water hammer phenomena, are difficult to detect due to their unique characteristics. Cavitation is one of the biggest threats to the effectiveness and structural integrity of water pumping systems, a process that arises from the creation and collapse of vapour bubbles in liquid phases (Hajnayeb et al., 2017). Cavitation is caused by low water pressure, prompting the formation of foam that can damage the impeller in the long term. In contrast, a water hammer is a hydraulic phenomenon that will cause a sudden pressure surge triggered by the closing of a valve or a change in fluid flow. This occurrence poses a significant risk to the pump and the integrity of the system. This situation makes the implementation of safety monitoring procedures and regular maintenance practices very critical.

It is important to acknowledge that MEMS accelerometers have been employed in fault detection for rotating machinery for many years (Mones et al., 2016; Feng et al., 2015; Adli & Rusmin, 2020). This study introduces a novel aspect by integrating the Arduino Mega 2560 with the ADXL345 accelerometer specifically for real-time monitoring of water pumps. This combination not only offers a cost-effective and accessible solution but also targets the detection of critical anomalies, such as cavitation and water hammer, which are essential for preserving the operational integrity of water pump systems. Unlike previous studies, this research highlights the practical application of widely available technology in cost-sensitive environments, where affordability and ease of deployment are vital considerations.

It is critical to comprehend these exacerbating variables as anomalies or pump damage are not always the same. Insufficient analysis of these intricate problems can impede the creation of effective treatment plans and prevention actions (Tian et al., 2022). The need for continuous monitoring also opens opportunities to predict or identify water pump anomalies before they become serious (Adeodu et al., 2020). By implementing an effective monitoring system, the pump maintenance team can take the necessary preventive actions before unwanted damage occurs. It provides an added advantage in maintaining the optimal performance of the pump system and ensuring uninterrupted operation. By emphasising the importance of water pump anomaly monitoring, this study seeks to provide a solid scientific and practical basis for the implementation of monitoring strategies in the daily operation of water pumping systems.

The vibration data acquired from the water pump motor holds significant value for analysis in maintenance management, particularly for implementing preventive or condition-based maintenance strategies. Preventive maintenance entails regular scheduling and continuous monitoring of equipment to forestall unforeseen breakdowns. The primary aim of scheduled maintenance is to maintain equipment in its optimal condition, ensuring optimal functionality and extending its operational lifespan for an extended period (Arunraj & Maiti, 2007; Smith & Hawkins, 2004). In contrast, condition-based maintenance relies on data collected during monitoring periods to determine suitable maintenance recommendations (Jardine et al., 2006). Maintenance tasks are performed upon reaching predetermined thresholds, guided by specific indicators identified beforehand. Neglecting the current state of the machine within the context of preventive or condition-based maintenance can elevate the risk of unexpected and inevitable machine failure, resulting in unnecessary expenditure (Zhou et al., 2005).

Several studies have explored vibration analysis methodologies for detecting anomalies in water pump maintenance, employing a range of methodologies and techniques. For instance, Sunal et al. (2022), Bai et al. (2019), and Sun et al. (2018) explored the use of vibration analysis coupled with machine learning algorithms to diagnose faults in centrifugal pumps. Guimarães and de Oliveira Filho (2021) also conducted a study focusing on detecting cavitation in water pumps using vibration analysis techniques. Their study successfully identified vibration components caused by cavitation in centrifugal pumps using the Power Spectrum and Continuous Wavelet Transform, improving hydraulic performance and pump life (Guimarães & de Oliveira Filho, 2021). Additionally, Lee and Le (2020) investigated the application of wavelet transform and envelope analysis for fault diagnosis in water pump bearings (Lee & Le, 2020).

Recently, a study by Al-Haddad et al. (2024) developed a sophisticated vibration-current data fusion approach combined with a gradient boosting classifier to enhance the diagnosis of stator faults in three-phase permanent magnet synchronous motors. Their work demonstrates the effectiveness of data fusion techniques in improving fault detection accuracy, which is crucial for maintaining the operational integrity of complex machinery. Similarly, Jaber and Bicker (2017) proposed a wireless fault detection system for industrial robots, leveraging statistical control charts to monitor and detect anomalies in real time. This approach highlights the growing trend toward integrating wireless technologies for more efficient and responsive fault detection. Additionally, Ogaili et al. (2023) focused on wind turbine blades, employing vibration dataset analysis to diagnose faults, further underscoring the importance of vibration analysis in predictive maintenance across different types of machinery. These studies collectively emphasise the critical role of advanced diagnostic techniques and real-time monitoring in ensuring the reliability and longevity of mechanical systems, providing a strong foundation for the present study's focus on vibration monitoring in water pumps. All the studies demonstrate the diverse approaches and methodologies employed to leverage vibration analysis for anomaly detection in water pump systems, highlighting the importance of this field in ensuring the reliability and efficiency of pump operations.

However, despite the insights gained from these studies, challenges persist with the widespread adoption of expensive vibration devices for Internet of Things (IoT) applications. These challenges, including security concerns and the feasibility of permanent installation at sites, underscore the need for alternative solutions. Given the limitations associated with costly vibration devices, there is a growing interest in exploring the feasibility of low-cost alternatives, such as Arduino microcontrollers, for vibration monitoring in water pump systems (Agnoletti et al., 2020). However, it is essential to acknowledge the limitations of such devices, which may impact their suitability for comprehensive monitoring. Arduino-based solutions often face constraints in terms of limited computational power and memory capacity, security vulnerabilities (Sainz-Raso et al., 2023), sampling rate, data transmission to the cloud, simultaneous measurement capabilities, accuracy, and sensitivity. These limitations can hinder their effectiveness in capturing nuanced vibration patterns and identifying subtle anomalies in pump operations. Thus, while Arduino devices offer affordability and accessibility, further research is needed to address these challenges and optimise their performance for reliable and robust vibration monitoring in real-world applications.

Studies on existing methods to detect water pump anomalies show the need to find more sophisticated and effective approaches. An introduction to recent developments in vibration sensors and monitoring technology provides insight into the potential use of inexpensive vibration sensors in water pump anomalies analysis (Ejimuda, 2020). This study evaluates the feasibility of utilising Arduino-based data acquisition to monitor water pump conditions using vibration analysis to identify anomalies. In this study, the anomalies were associated with cavitation, as shown in the results. The research involved the development of a vibration measurement apparatus employing an Arduino Mega 2560 and ADXL345 accelerometer, which was installed on a water pump motor for monitoring purposes. Through Wi-Fi connectivity, the device facilitated online monitoring by transmitting vibration data in real time, enabling the detection of anomalies such as water hammer and cavitation problems.

METHODOLOGY

This study evaluates the feasibility of using Arduino for measurement by considering several important factors. One key aspect is the choice of the Administration Building of the Engineering Faculty at Universiti Putra Malaysia as the study site, which offers a practical and real-world environment for testing the Arduino-based monitoring system. The presence of two units of similar Vertical Multistage centrifugal-type water pumps (Figure 1) operating alternately in the building offers a suitable setting to assess the effectiveness and reliability of the Arduino system in monitoring pump performance over an extended period. The specifications of the water pumps, including their power ratings, operating speeds, and flow rates, serve as crucial parameters for

(a) (b)

Figure 1. (a) Water pump No.1; and (b) Water pump No.2

evaluating the compatibility and capability of the Arduino platform for capturing relevant data accurately.

As previously mentioned, two units of similar Vertical Multistage centrifugal-type water pumps are utilised for the building, operating alternately. The specifications of these water pumps are detailed in Table 1.

The methodology of this project includes device design for data acquisition, device verification, the installation of the device, and the analysis of the data. The device is set using an Arduino Mega 2560 microcontroller and ADXL345 accelerometer called Arduino Data Acquisition system (ADAQ), divided into:

- Design and Development of ADAQ
- ADAQ Verification
- ADAQ Installation on Water Pumps Motor
- Data analysis

Table 1
Water pump specifications and electric motor specifications

Water Pump Specifications		**Electric Motor Specifications**	
Model	BUGATI CVM10-8	Model	YE2-90LA-2
H_{max}	84 m	Power	3.0 kW, 50Hz
H_N	62 m	Voltage	240/415V
QN	10m3/h	Ampere	9.8/5.7A
P2	3.0kW, 50Hz	Efficiency	84.6%
Rotation Speed	2900 r/min	Rotation Speed	2900 r/min

Design and Development of ADAQ

The design process began with defining the system requirements and selecting appropriate components to meet these requirements. Key considerations included ensuring compatibility between the Arduino Mega 2560 and the ADXL345 accelerometer, as well as integrating additional components for comprehensive functionality. Challenges faced during the design process included optimising data sampling rates and ensuring reliable data transmission. Careful accelerometer calibration was performed to address these challenges, and the software was programmed to handle data storage and transmission efficiently. ADAQ integrates an Arduino Mega 2560 microcontroller and an ADXL345 accelerometer, facilitating real-time data collection and analysis. Additional components include a microSD card adapter, a clock module, and an ESP8266 Wi-Fi module for internet connectivity. All components are shown in Figure 2, and their functions are listed in Table 2. The integration of these components required meticulous wiring and configuration to ensure proper communication and data flow. The ADAQ setup enables efficient monitoring of vibration levels in three axes (X, Y, Z) to assess pump performance.

Table 2
Arduino data acquisition system components

Component	Function
Arduino MEGA: ESP8266WiFi Module microcontroller	Processing and sending data with internet connection capability
ADXL345 Accelerometer	Measure vibration in three axes
SD Card	Saving the raw data into micro–SD Card
Clock module	To link measurement with real-time
Base Shield v2	For easy connection between sensors and Arduino
LCD 16×2	To display selected output

The ADXL345 accelerometer could sample at a maximum rate of 530 points per second, which was limited by the components, instructions and ability of the microcontroller. The samples taken per measurement were set to 299 points per second to accommodate the dynamic memory's limitations to optimise data collection. Additionally, challenges related to ensuring stable and accurate sampling were addressed through thorough testing and adjustment of the sampling parameters.

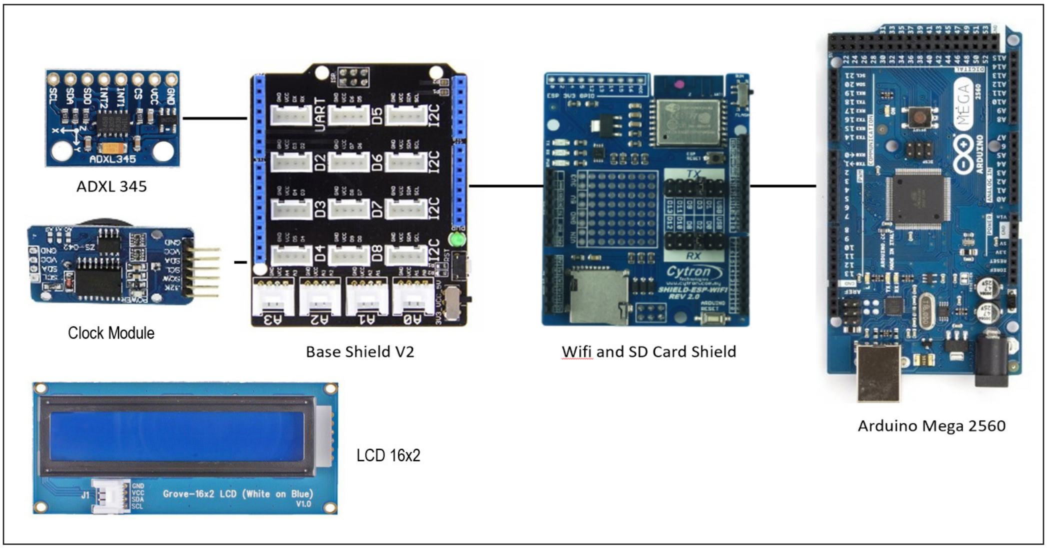

Figure 2. ADAQ component

ADAQ Verification

The verification of ADAQ's performance and accuracy is based on a previous study that utilised the same ADAQ configuration and ADXL345 accelerometer. This study conducted random vibration measurements using the ADAQ and the National Instruments Data Acquisition System (NI DAQ), with vibration frequencies ranging from 10 to 150 Hz

(Rezali et al., 2022). Challenges encountered during verification included aligning the data from different systems and ensuring consistency across measurements. To overcome these issues, calibration procedures were implemented, and a comparative analysis was conducted to validate the accuracy of the ADAQ. The results indicated that the data obtained were reliable, showing differences of less than 10% (Rezali et al., 2022).

ADAQ Installation on Water Pump Motor

The installation of ADAQ on water pump motors involved mounting the ADXL345 accelerometer on each pump to measure vibration levels, as shown in Figure 3. It allowed for real-time monitoring of pump vibrations in the water pump room. During installation, challenges included ensuring the secure placement of the accelerometer and minimising potential interference from other equipment—solutions involved using appropriate mounting techniques and shielding to enhance measurement accuracy. Vibration measurements were converted to root-mean-square (RMS) acceleration values and transmitted to the cloud system for analysis. Additionally, raw vibration data was stored on the microSD card for further offline analysis.

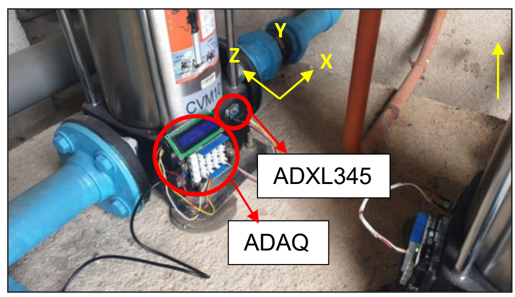

Figure 3. ADAQ installation at the water pump motor showing all axes' direction

Data Analysis

In the data analysis phase, vibration measurements obtained from ADAQ were subjected to time-domain and frequency-domain analyses to evaluate the vibration characteristics of the water pumps. Initially, the raw data were processed to calculate the Root Mean Square (RMS) values, which were then sent to the cloud for monitoring. The RMS value, a key indicator of vibration intensity, was computed using the following Equation 1:

$$RMS = \sqrt{\frac{1}{n}\sum_{i} x_i^2} \qquad [1]$$

Where n is the number of data points, and $\boldsymbol{x_i}$ represents each individual vibration measurement point.

During data analysis, additional challenges included handling large data sets and ensuring accurate interpretation of vibration patterns. These challenges were addressed through the use of robust data processing techniques and validation against known benchmarks. Subsequently, the data underwent time-domain and frequency-domain analyses. Time-domain analysis provided insights into vibration intensity and patterns over time, while frequency-domain analysis identified dominant frequencies, including the blade pass frequency (BPF). For frequency-domain analysis, the Welch method was employed using MATLAB, a widely used technique for signal processing power spectral density (PSD) estimation. This method provided a robust and accurate frequency-domain analysis, which, when combined with the time-domain analysis, offered a comprehensive understanding of the vibration characteristics of the water pumps.

The results of data analysis facilitated the identification of normal and abnormal operating conditions, aiding in the diagnosis of potential pump malfunctions or inefficiencies. In summary, the methodology outlined in this study ensures systematic data collection, verification, and analysis, enabling a comprehensive assessment of water pump performance and operational integrity.

RESULT AND DISCUSSION

Daily Vibration Measured at the Water Pump

Figures 4, 5, and 6 show vibration data measured at the water pump for 3 days before, during, and after the detected anomalies. The RMS value on 1st April 2023 did not fluctuate much and was stable throughout the day. The RMS values of all the axes were not significantly different, with the maximum amplitude value at 0.82 m/s^2.

On 3rd April 2023, the RMS vibration values in the x, y, and z axes surged to higher-than-normal levels compared to the previous operational period, beginning around 11:37 a.m., immediately after the pump restarted (Figure 5). This abnormal vibration continued on 4th April 2023, with the maximum RMS vibration value reaching up to 2.89 m/s^2, as

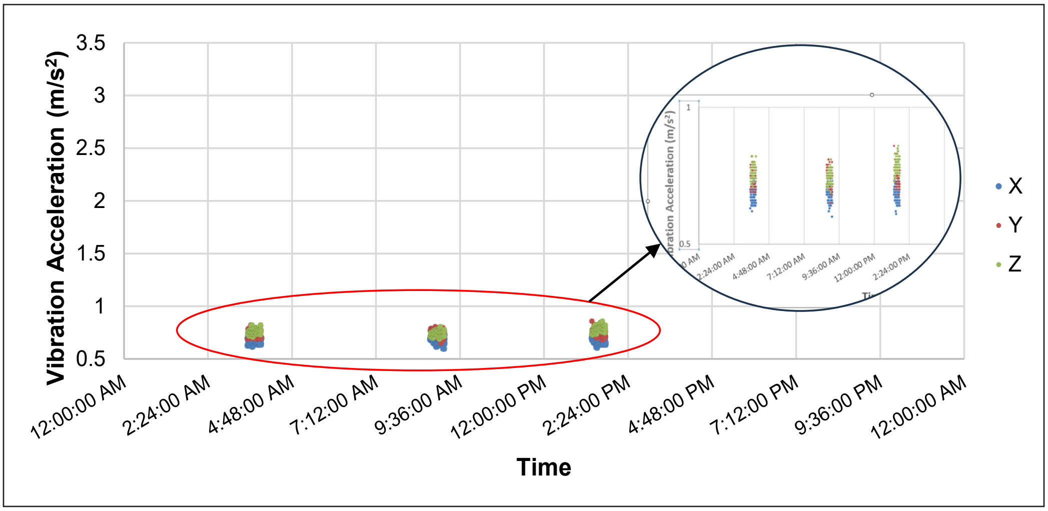

Figure 4. Vibration measured at the water pump on 1st April 2023

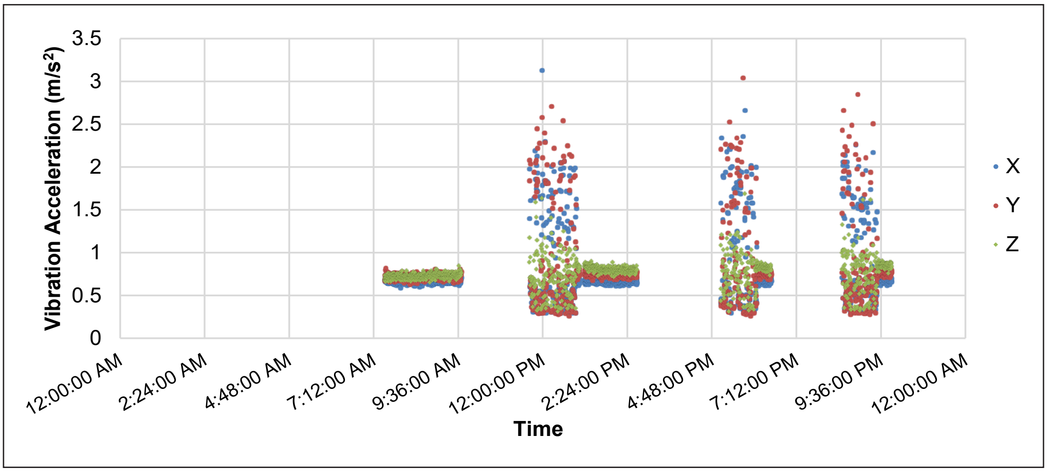

Figure 5. Vibration measured at the water pump on 3rd April 2023

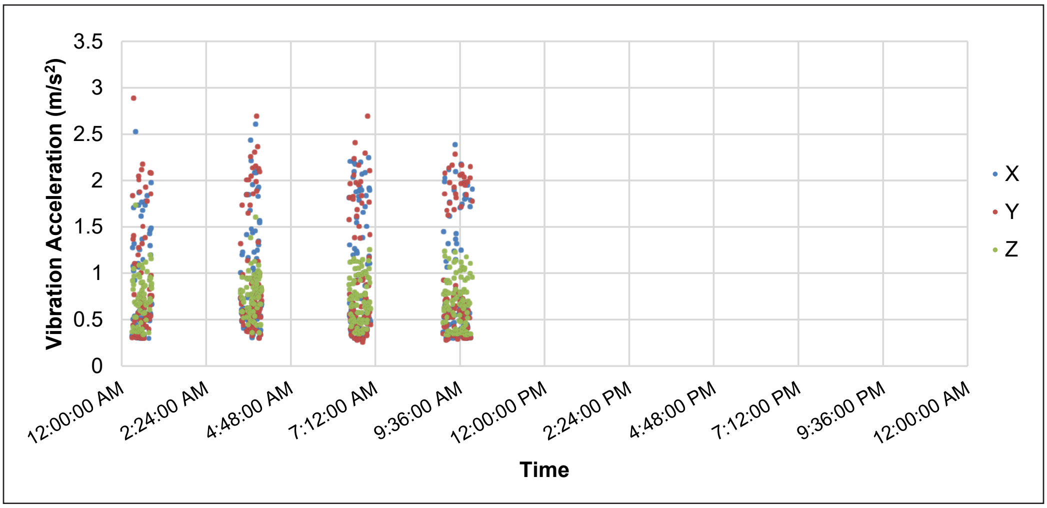

Figure 6. Vibration measured at the water pump on 4th April 2023

depicted in Figure 6. Subsequently, the pump was shut off and scheduled for maintenance and repair work.

Time Domain and Frequency Domain Vibration of the Water Pump

The summary of RMS values for the X, Y, and Z axes during normal (Figure 7) conditions and abnormal conditions (Figure 8) reveals distinct patterns. In normal conditions, the RMS values are relatively low: X=0.3698 m/s^2, Y=0.4064 m/s^2, and Z=0.3804 m/s^2 indicating minimal vibration intensity along each axis. Conversely, notably higher RMS values are observed during abnormal conditions: X=1.0365 m/s^2, Y=1.1342 m/s^2, and Z=0.5912 m/s^2.

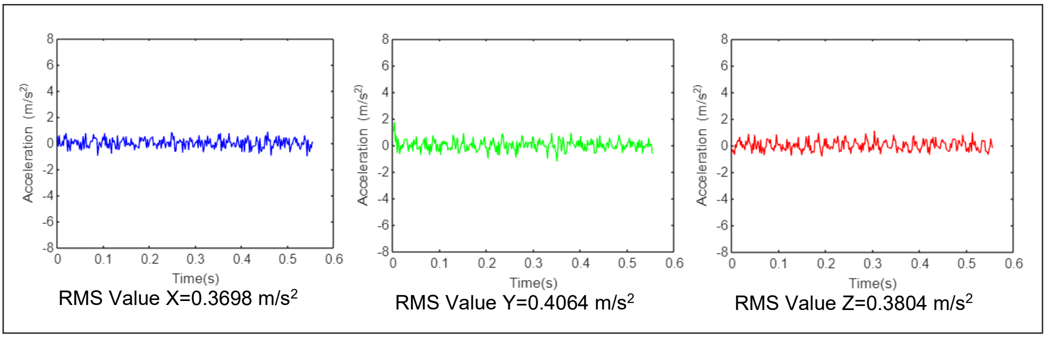

Figure 7. Vibration acceleration (time domain)—NORMAL CONDITION

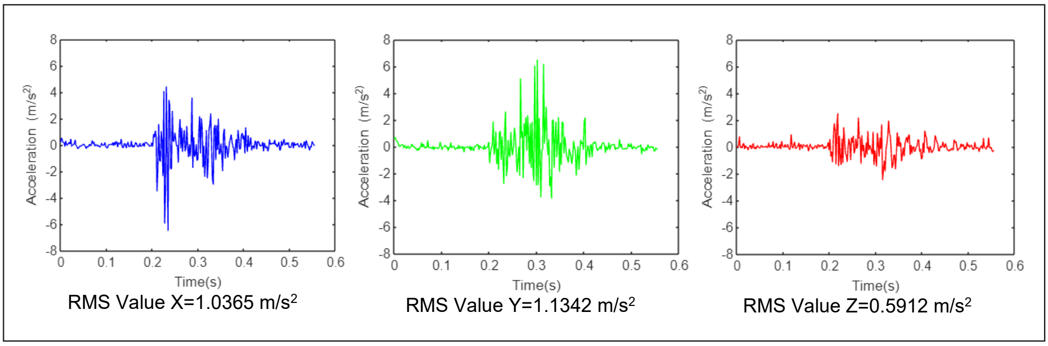

Figure 8. Vibration acceleration (time domain)—ABNORMAL CONDITION

This significant increase in RMS values suggests a substantial amplification of vibration intensity across all axes during abnormal conditions. Moreover, the time domain graphs corroborate these findings, showing a distinct pattern of sporadic spikes in vibration intensity during abnormal conditions, contrasting with the smoother, more uniform pattern observed during normal conditions. This discrepancy underscores the efficacy of RMS values as indicators of abnormal vibration behaviour, with higher RMS values corresponding to pronounced irregularities in vibration patterns. These results suggest that monitoring RMS values provides a reliable method for detecting and distinguishing between normal and abnormal conditions in vibration analysis, facilitating timely intervention to prevent potential equipment malfunction or failure.

The frequency domain analysis shows distinct differences between normal and abnormal conditions. During normal conditions, the graph prominently displays the blade pass frequency (BPF) or 1× frequency across all axes, with the occasional presence of higher harmonics up to 5× frequency on certain axes (Figure 9). This characteristic pattern is indicative of stable and consistent machinery operation. However, in the abnormal frequency domain graph, while BPF remains discernible, the graph exhibits irregularities above the BPF, manifesting as random frequencies (Figure 10). This deviation from the expected pattern suggests the presence of anomalous vibration behaviour, potentially attributable to cavitation effects. Cavitation was induced by operating the pump under conditions of low NPSH (Net Positive Suction Head) and high flow rates, which promote cavitation (Sanchez et al., 2018). Verification of cavitation involved observing the characteristic changes in vibration frequency and amplitude patterns consistent with the symptoms of cavitation described in the literature (Hajnayeb et al., 2017; Abdulaziz & Kotb, 2017). Cavitation-induced irregularities in the frequency domain graph serve as a critical indicator of machinery malfunction or inefficiency, highlighting the importance of frequency domain analysis in detecting and diagnosing operational abnormalities in mechanical systems.

The analysis of vibration velocity in the time domain reveals notable differences between normal and abnormal conditions. During normal conditions, the RMS values for vibration velocity are relatively low: X=0.8790 m/s, Y=1.3213 m/s, and Z=1.1997 m/s, indicating moderate vibration intensity along each axis (Figure 11). Conversely, during abnormal conditions, significantly higher RMS values are observed: X=2.2012 m/s, Y=2.2940 m/s, and Z=1.5368 m/s, indicating a substantial amplification of vibration intensity across all axes (Figure 12). This consistent pattern persists even when converting from acceleration to velocity, underscoring the persistence of abnormal vibration behaviour across different domains. Such pronounced differences in vibration velocity between normal and abnormal

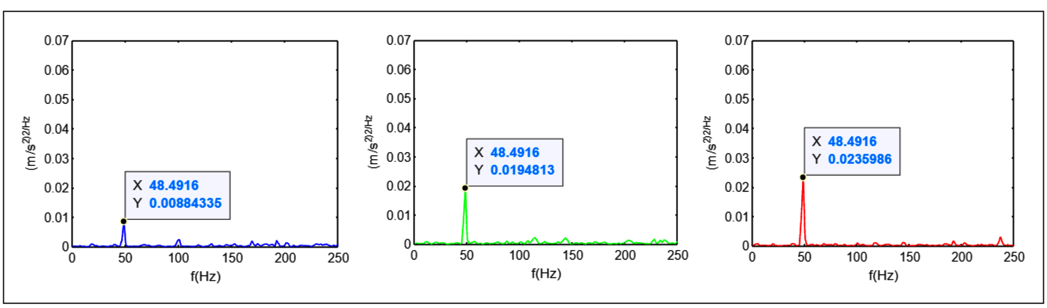

Figure 9. Vibration acceleration (frequency domain)—NORMAL CONDITION

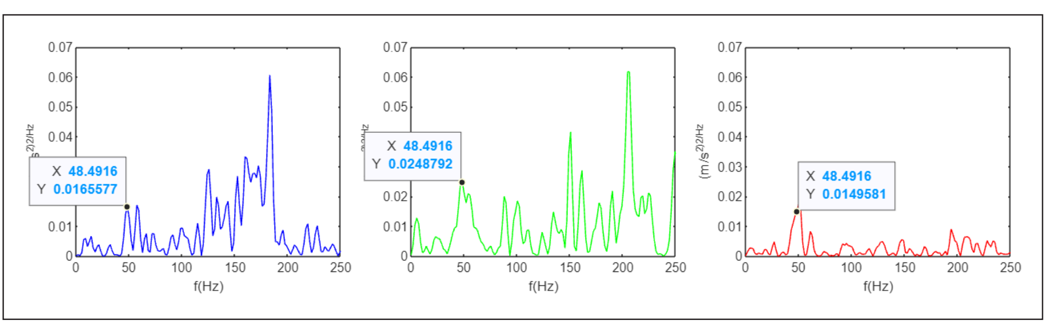

Figure 10. Vibration acceleration (frequency domain)—ABNORMAL CONDITION

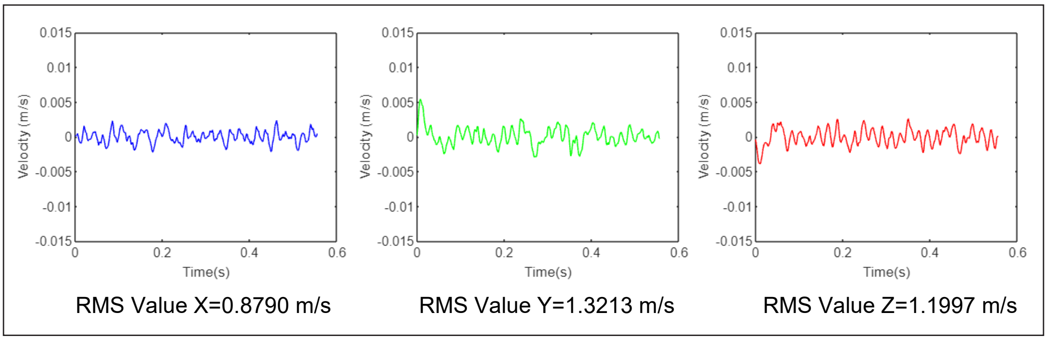

Figure 11. Vibration velocity (time domain)—NORMAL CONDITION

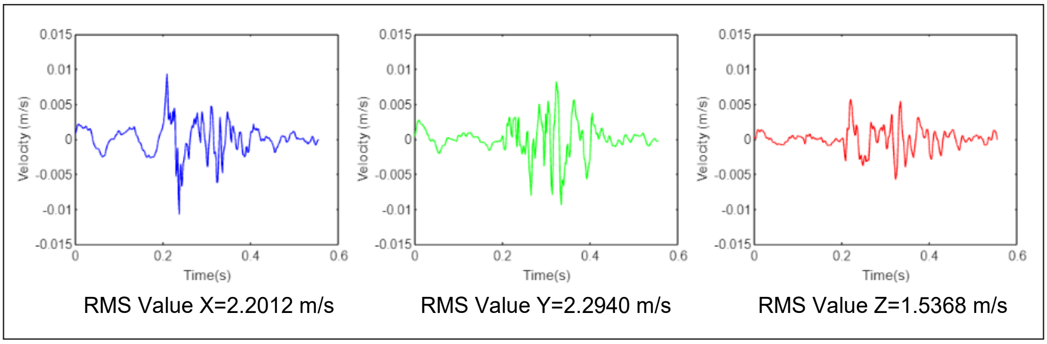

Figure 12. Vibration velocity (time domain)—ABNORMAL CONDITION

conditions highlight the potential severity of operational irregularities, necessitating prompt attention and intervention to mitigate potential equipment damage or failure.

In the frequency domain analysis of vibration velocity, distinct differences between normal and abnormal conditions emerge. During normal conditions, the blade pass frequency (BPF) remains clearly identifiable across all axes, indicating stable machinery operation (Figure 13). However, during abnormal conditions, while the BPF is still discernible in the X axis at 48.4916 Hz, significant alterations occur in the Y and Z axes, where the BPF shifts to 46.6957 Hz and 52.0836 Hz, respectively (Figure 14). This deviation in BPF frequencies across axes suggests irregularities in machinery operation, potentially indicative of underlying faults or inefficiencies. The changes in BPF frequencies align with known symptoms of cavitation, which typically affects the frequency spectrum and can shift the BPF due to changes in the pump (Kafeel et al., 2021). However, the absence of frequency peaks above the BPF complicates fault determination, as vibration velocities beyond the BPF fail to provide conclusive indications of pump system malfunctions. It underscores the limitations of using vibration velocity in the frequency domain for fault diagnosis in such monitoring scenarios, necessitating complementary diagnostic approaches for comprehensive system assessment.

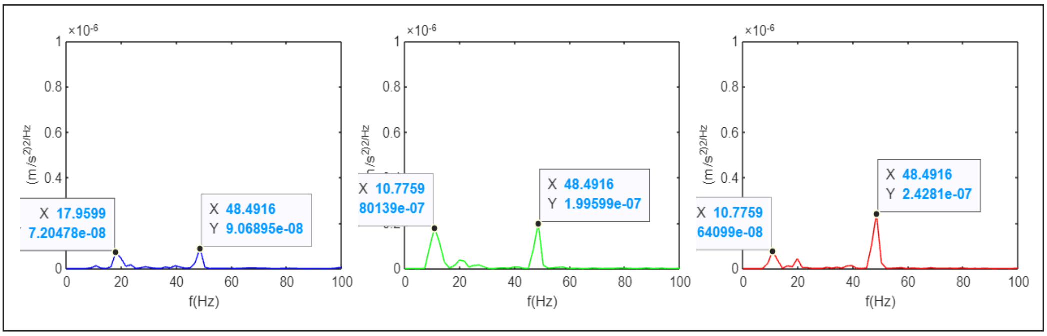

Figure 13. Vibration velocity (frequency domain)—NORMAL CONDITION

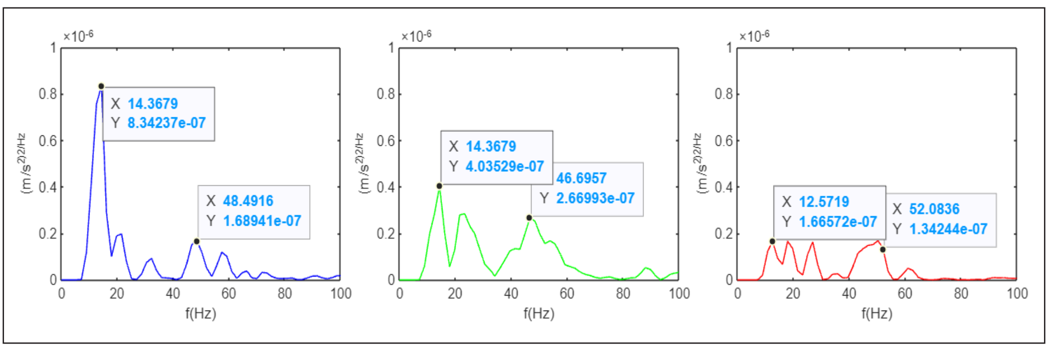

Figure 14. Vibration velocity (frequency domain)—ABNORMAL CONDITION

Vibration Spectrogram Graph

Based on the raw data, vibration spectrograms were generated for normal and abnormal conditions across all axes (Figure 15). During normal conditions, the spectrograms clearly indicate the blade pass frequency (BPF) in all axes, with additional harmonics observed up to 5 × frequency on the X and Z axes. This consistent pattern suggests stable machinery operation and a well-defined frequency distribution. However, in abnormal spectrogram graphs, the smoothness of the graph is notably disrupted, indicating irregularities in vibration patterns. These disruptions are consistent with cavitation effects, which can cause fluctuating and erratic patterns in the spectrogram. These disruptions may signify the presence of anomalies or faults within the system, potentially leading to inefficiencies or malfunctions. Further analysis of the abnormal spectrogram graphs is warranted to pinpoint the specific nature and severity of these irregularities, facilitating timely intervention and maintenance to ensure optimal system performance and reliability.

The investigation into vibration patterns in both time and frequency domains, alongside spectrogram data analysis, reveals key findings consistent with prior research. Under normal operating conditions, stable machinery performance is indicated by consistent patterns

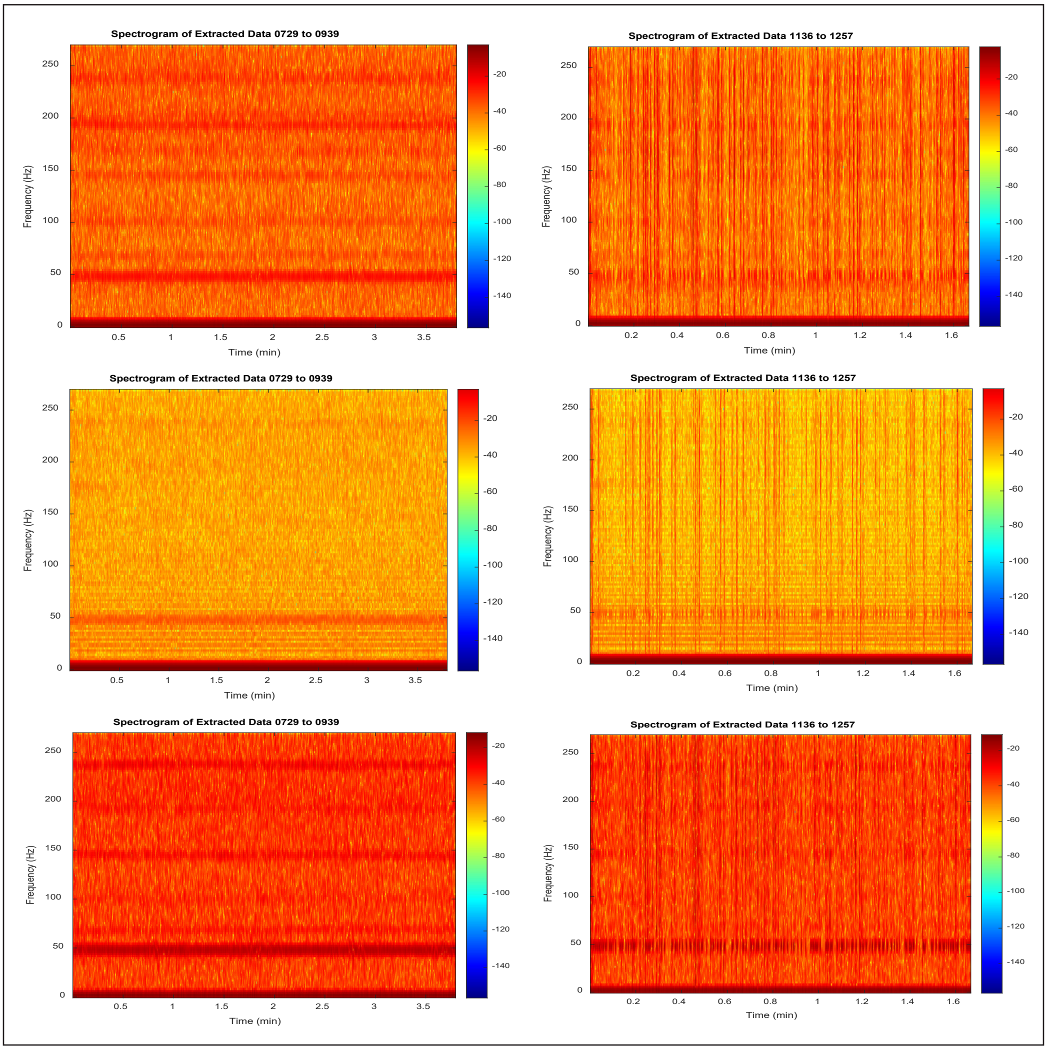

Figure 15. Vibration spectrogram graph during NORMAL conditions (left) and ABNORMAL conditions (right) for all axes, respectively

across various axes, including blade pass frequency (BPF) and harmonics (Bai et al., 2019). Conversely, abnormal conditions exhibit significant deviations from these established patterns, manifesting irregularities in vibration intensity and frequency distribution (Karagiovanidis et al., 2023). This discrepancy suggests the presence of anomalies or faults within the system, aligning with previous studies investigating factors such as cavitation or mechanical wear (Krishnachandran et al., 2020). Furthermore, the limitations of vibration velocity analysis in the frequency domain for fault diagnosis underscore the need for complementary diagnostic approaches. Overall, the comprehensive analysis of vibration data reveals valuable insights into the operational status of the pump system, highlighting the importance of continuous monitoring and proactive maintenance to ensure optimal performance and reliability.

The outcomes of this study represent a significant advancement in the domain of water pump monitoring, particularly in the context of cavitation detection. The amalgamation of the ADXL345 accelerometer with Arduino Mega2560 has demonstrated its practicality and affordability in discerning irregularities within water pumps during operational phases (Hasibuzzaman et al., 2020). Specifically, the discernible rise in mean amplitude (RMS) during cavitation occurrences, compared to normal conditions, is a robust indicator of anomalous pump activity. This finding holds paramount importance as it furnishes a precise and quantifiable parameter for identifying cavitation, a phenomenon notorious for its detrimental effects on pump components.

However, it is important to note that while the Arduino Mega2560 coupled with the ADXL345 accelerometer shows promise, a direct comparison with other commercially available or research-grade vibration monitoring systems was not conducted in this study. Prior research, such as the work by Al-Haddad et al. (2024), has demonstrated the effectiveness of advanced vibration-current data fusion techniques and sophisticated classifiers like gradient boosting for enhanced fault detection in motors, suggesting that more complex systems may offer improved accuracy. Similarly, Jaber and Bicker (2017) highlight the potential of wireless fault detection systems that utilise statistical control charts to achieve real-time monitoring in industrial environments. Such comparisons would be valuable in assessing the relative performance, accuracy, and cost-effectiveness of the Arduino-based system. This gap presents an opportunity for future research to benchmark the system against established technologies, which could further validate its potential for broader industrial adoption.

The findings of this study not only validated the viability of Arduino Mega2560 coupled with the ADXL345 accelerometer for cavitation detection but also presented prospects for cost-effective and efficacious monitoring of water pump systems across various applications. However, while the affordability of the Arduino-based system is an important consideration, it is crucial to note that this study does not delve into a detailed cost-benefit analysis. The primary objective of this research is to evaluate the technical capability of the Arduino Mega2560 and MEMS accelerometer in capturing real-time faults within a water pump system. A comprehensive cost-benefit analysis, though valuable, falls outside the scope of this work and is suggested as an area for future research. The emphasis here remains on demonstrating the system's ability to detect faults reliably and efficiently, contributing to its potential application in various industrial contexts where real-time monitoring is essential. This research lays the groundwork for the integration of readily available technology into industrial contexts, fostering a proactive approach towards pump maintenance and system integrity.

CONCLUSION

This study demonstrated the effectiveness of the ADAQ in accurately monitoring the vibration conditions within water pump motors. By employing the Fast Fourier Transform (FFT) method and incorporating spectrogram analysis, valuable insights into pump performance and anomalies were obtained, laying the groundwork for proactive maintenance strategies. The integration of ADAQ offers a reliable approach for assessing water pump operational integrity and holds potential for predictive maintenance in industrial settings. However, while the current methodology has proven effective, there are opportunities for further refinement and enhancement.

Future research could explore the integration of advanced machine learning algorithms to further improve the accuracy and reliability of anomaly detection in vibration data. These algorithms could be trained to recognise subtle patterns that may precede mechanical failures, allowing for even earlier intervention. Additionally, expanding the ADAQ system to include real-time monitoring capabilities and wireless data transmission would increase its applicability in more complex industrial environments. Another potential area for improvement is the incorporation of multi-sensor fusion, which would allow for a more comprehensive assessment of pump health by combining data from multiple types of sensors, such as temperature, pressure, and flow rate, alongside vibration data.

Moreover, the current study primarily focused on detecting cavitation-related anomalies. Future studies could investigate the applicability of the ADAQ system to detect other common faults in water pumps, such as misalignment, imbalance, and bearing defects. This would further validate and expand the versatility of the ADAQ in various operational contexts.

In conclusion, while the ADAQ system has demonstrated significant potential in water pump monitoring, future research directions and improvements will contribute to developing even more robust and sophisticated vibration monitoring systems, ultimately leading to optimised maintenance practices and increased operational reliability in water pump operations.

ACKNOWLEDGMENTS

The first author sincerely thanks the Public Service Department of Malaysia for their scholarship support. The authors also express their gratitude to the Public Works Department Malaysia for the research funding provided for this project and to the University Putra Malaysia for its laboratory facilities and expertise.

REFERENCES

Abdulaziz, A. M., & Kotb, A. (2017). Detection of pump cavitation by vibration signature. *Australian Journal of Mechanical Engineering*, *15*(2), 103–110. https://doi.org/10.1080/14484846.2015.1093261

Adeodu, A., Daniyan, I., Omitola, O., Ejimuda, C., Agbor, E., & Akinola, O. (2020). An adaptive industrial internet of things (IIoTs) based technology for prediction and control of cavitation in centrifugal pumps. *Procedia CIRP*, *91*, 927–934. https://doi.org/10.1016/j.procir.2020.03.125

Adli, B., & Rusmin, P. H. (2020). Vibration measuring tools for rotary pumping machine with accelerometer MEMS sensor. In *2020 FORTEI-International Conference on Electrical Engineering (FORTEI-ICEE)* (pp. 69-74). IEEE Publishing. https://doi.org/10.1109/FORTEI-ICEE50915.2020.9249860

Agnoletti, L., Pedotti, S., Zago, R. M., Giesbrecht, M., & Fruett, F. (2020). Low-cost MEMS accelerometer network for rotating machine vibration diagnostics analyzing machine vibration. *IEEE Instrumentation & Measurement Magazine, 23*(7), 25-33. https://doi.org/10.1109/MIM.2020.9234762

Al-Haddad, L. A., Jaber, A. A., Hamzah, M. N., & Fayad, M. A. (2024). Vibration-current data fusion and gradient boosting classifier for enhanced stator fault diagnosis in three-phase permanent magnet synchronous motors. *Electrical Engineering*, *106*(3), 3253–3268. https://doi.org/10.1007/s00202-023-02148-z

Altherr, L. C., Leise, P., Pfetsch, M. E., & Schmitt, A. (2019). Resilient layout, design and operation of energy-efficient water distribution networks for high-rise buildings using MINLP. *Optimization and Engineering*, *20*(2), 605–645. https://doi.org/10.1007/s11081-019-09423-8

ALTobi, M. A. S., Bevan, G., Wallace, P., Harrison, D., & Ramachandran, K. P. (2019). Centrifugal pump condition monitoring and diagnosis using frequency domain analysis. In *Applied Condition Monitoring* (Vol. 15, pp. 122–131). Springer. https://doi.org/10.1007/978-3-030-11220-2_13

Arunraj, N. S., & Maiti, J. (2007). Risk-based maintenance-Techniques and applications. *Journal of Hazardous Materials*, *142*(3), 653–661. https://doi.org/10.1016/j.jhazmat.2006.06.069

Bai, L., Zhou, L., Jiang, X., Pang, Q., & Ye, D. (2019). Vibration in a multistage centrifugal pump under varied conditions. *Shock and Vibration*, *2019*, 1–9. https://doi.org/10.1155/2019/2057031

Chen, L., Wei, L., Wang, Y., Wang, J., & Li, W. (2022). Monitoring and predictive maintenance of centrifugal pumps based on smart sensors. *Sensors*, *22*(6), Article 2106. https://doi.org/10.3390/s22062106

Dutta, N., Kaliannan, P., & Subramaniam, U. (2020). Effect of motor vibration problems on power quality of water pumping at residency. *IOP Conference Series: Materials Science and Engineering*, *937*(1), Article 012019. https://doi.org/10.1088/1757-899X/937/1/012019

Ejimuda, C. (2020). Development and prediction of cavitation in centrifugal pumps using industrial internet of things technology. In *SPE Nigeria Annual International Conference and Exhibition* (p. D013S006R012). SPE Publishing. https://doi.org/10.2118/203661-MS

Feng, G. J., Gu, J., Zhen, D., Aliwan, M., Gu, F. S., & Ball, A. D. (2015). Implementation of envelope analysis on a wireless condition monitoring system for bearing fault diagnosis. *International Journal of Automation and Computing*, *12*(1), 14–24. https://doi.org/10.1007/s11633-014-0862-x

Guimarães, T. A., & de Oliveira Filho, R. H. (2021). Analysis of vibration signals produced by the cavitation in centrifugal pumps using the Power Spectrum and Continuous Wavelet Transform. *Revista Brasileira de Ciência, Tecnologia e Inovação*, *5*(1), 1-12. https://doi.org/10.18554/rbcti.v5i1.3413

Hajnayeb, A., Azizi, R., Ghanbarzadeh, A., & Changizian, M. (2017). Vibration-based cavitation detection in centrifugal pumps. *Diagnostyka*, *18*(3), 77–83.

Hasibuzzaman, M., Shufian, A., Shefa, R. K., Raihan, R., Ghosh, J., & Sarker, A. (2020). Vibration measurement & analysis using arduino based accelerometer. In *2020 IEEE Region 10 Symposium (TENSYMP)* (pp. 508-512). IEEE Publishing. https://doi.org/10.1109/TENSYMP50017.2020.9230668

Jaber, A. A., & Bicker, R. (2017). Wireless fault detection system for an industrial robot based on statistical control chart. *International Journal of Electrical and Computer Engineering*, *7*(6), 3421–3435. https://doi.org/10.11591/ijece.v7i6.pp3421-3435

Jardine, A. K. S., Lin, D., & Banjevic, D. (2006). A review on machinery diagnostics and prognostics implementing condition-based maintenance. *Mechanical Systems and Signal Processing*, *20*(7), 1483–1510. https://doi.org/10.1016/j.ymssp.2005.09.012

Kafeel, A., Aziz, S., Awais, M., Khan, M. A., Afaq, K., Idris, S. A., Alshazly, H., & Mostafa, S. M. (2021). An expert system for rotating machine fault detection using vibration signal analysis. *Sensors*, *21*(22), Article 7587. https://doi.org/10.3390/s21227587

Karagiovanidis, M., Pantazi, X. E., Papamichail, D., & Fragos, V. (2023). Early detection of cavitation in centrifugal pumps using low-cost vibration and sound sensors. *Agriculture*, *13*(8), Article 1544. https://doi.org/10.3390/agriculture13081544

Kiliç, R., Kozan, R., Karayel, D., & Özkan, S. S. (2017). Application of predictive maintenance system in drinking water pumping stations. *Acta Physica Polonica A*, *132*(3), 1016–1021. https://doi.org/10.12693/APhysPolA.132.1016

Kondaveeti, H. K., Kumaravelu, N. K., Vanambathina, S. D., Mathe, S. E., & Vappangi, S. (2021). A systematic literature review on prototyping with arduino: Applications, challenges, advantages, and limitations. *Computer Science Review*, *40*, Article 100364. https://doi.org/10.1016/j.cosrev.2021.100364

Krishnachandran, Samson, A., & Rajan, A. (2020). Condition monitoring of cavitation-induced centrifugal pump. In A. Suryan, D. H. Doh, M. Yaga & G. Zhang (Eds.), *Recent Asian Research on Thermal and Fluid Sciences* (pp. 393–408). Springer. https://doi.org/10.1007/978-981-15-1892-8_31

Lee, C. Y., & Le, T. A. (2020). Intelligence bearing fault diagnosis model using multiple feature extraction and binary particle swarm optimization with extended memory. *IEEE Access*, *8*, 198343–198356. https://doi.org/10.1109/ACCESS.2020.3035081

Lourenço, M., Silva-Afonso, A., & Pimentel-Rodrigues, C. (2022). Performance indicators for water supply in buildings. *WSEAS Transactions on Environment and Development*, *18*, 1115–1128. https://doi.org/10.37394/232015.2022.18.106

Midiani, L. P. I., Irawan, I. M. D., Bangse, K., & Gunung, I. N. (2023). Design of clean water booster pump for high-rise buildings. *LOGIC: Jurnal Rancang Bangun Dan Teknologi*, *23*(3), 203–211. https://doi.org/10.31940/logic.v23i3.203-211

Mones, Z., Feng, G., Ogbulaor, U. E., Wang, T., Gu, F., & Ball, A. D. (2016). Performance evaluation of wireless MEMS accelerometer for reciprocating compressor condition monitoring. In *Power Engineering: Proceedings of the International Conference on Power Transmissions 2016 (ICPT 2016)* (pp. 893-900). Taylor & Francis. https://doi.org/10.1201/9781315386829-129

Ogaili, A. A. F., Jaber, A. A., & Hamzah, M. N. (2023). Wind turbine blades fault diagnosis based on vibration dataset analysis. *Data in Brief*, *49*, Article 109414. https://doi.org/10.1016/j.dib.2023.109414

Pan, T., & Zhu, Y. (2018). Getting started with Arduino. In T. Pan & Y. Zhu (Eds.), *Designing Embedded Systems with Arduino* (pp. 3–16). Springer. https://doi.org/10.1007/978-981-10-4418-2_1

Rezali, K. A. M., Rahim, S. A., Hassan, A. B. M., Abidin, A. M. Z., Khalid, S. N. A., & Mohd, A. B. (2022, July 24-28). *Development of an Arduino data acquisition system for condition-based monitoring* [Paper Presentation]. Proceedings of the International Congress on Sound and Vibration, 28th International Congress on Sound and Vibration, ICSV, Singapore.

Smith, R., & Hawkins, B. (2004). *Lean maintenance: Reduce costs, improve quality, and increase market share*. Elsevier.

Sainz-Raso, J., Martin, S., Diaz, G., & Castro, M. (2023). Security management on arduino-based electronic devices. *IEEE Consumer Electronics Magazine*, *12*(3), 72–84. https://doi.org/10.1109/MCE.2022.3184118

Sanchez, W., Carvajal, C., Poalacin, J., & Salazar, E. (2018). Detection of cavitation in centrifugal pump for vibration analysis. In *2018 4th International Conference on Control, Automation and Robotics (ICCAR)* (pp. 460-464). IEEE Publishing. https://doi.org/10.1109/ICCAR.2018.8384720

Shibnauth, V. D., & Surnam, B. Y. R. (2015, April 20-21). *Issues affecting water distribution systems* [Paper Presentation]. International Conference on Computer Science, Data Mining & Mechanical Engineering (ICCDMME), Bangkok, Thailand. https://doi.org/10.15242/IIE.E0415025

Sun, H., Yuan, S., & Luo, Y. (2018). Cyclic spectral analysis of vibration signals for centrifugal pump fault characterization. *IEEE Sensors Journal*, *18*(7), 2925–2933. https://doi.org/10.1109/JSEN.2018.2804908

Sunal, C. E., Dyo, V., & Velisavljevic, V. (2022). Review of machine learning based fault detection for centrifugal pump induction motors. *IEEE Access*, *10*, 71344–71355. https://doi.org/10.1109/ACCESS.2022.3187718

Tian, Q., Lin, C., Hu, R., Ya, C., & Xu, S. (2022). Numerical and experimental investigations on cavitation characteristics of inducer and impeller combination fuel pumps. In *CSAA/IET International Conference on Aircraft Utility Systems (AUS 2022)* (Vol. 2022, pp. 1369-1376). IET Publishing. https://doi.org/https://doi.org/10.1049/icp.2022.1872

Van Der Schee, W. G. (2009, September 7-9). *Water systems in high rise residential buildings, guidelines for design and construction.* [Paper Presentation]. The 35th International Symposium CIB W062 on Water Supply and Drainage for Buildings, Düsseldorf, Germany.

Yehl, C. C., Member, S., Sizovl, G. Y., Sayed-Ahmed, A., Povinellil, R. J., Member, S., Yazl, E. E., & Ionel, D. M. (2008). A reconfigurable motor for experimental emulation of stator winding inter-turn and broken bar faults in polyphase induction machines. *IEEE Transactions on Energy Conversion*, *23*(2), 1005–1014. https://doi.org/10.1109/TEC.2007.914201

Zhou, J., Li, X., Andernroomer, A. J., Zeng, H., Goh, K. M., Wong, Y. S., & Hong, G. S. (2005). Intelligent prediction monitoring system for predictive maintenance in manufacturing. In *31st Annual Conference of IEEE Industrial Electronics Society, 2005. IECON 2005* (pp. 6-pp). IEEE Publishing. https://doi.org/10.1109/IECON.2005.1569264

Zhou, Y., Lee, E. W. M., Wong, L. T., & Mui, K. W. (2021). Environmental evaluation of pump replacement period in water supply systems of buildings. *Journal of Building Engineering, 40*, Article 102750. https://doi.org/10.1016/j.jobe.2021.102750