LOW-COST VIBRATION MONITORING SYSTEM FOR GEAR-TYPE HYDRAULIC PUMPS TO SUPPORT PREDICTIVE MAINTENANCE

Daniel-Vasile BANYAI[1], Ioan-Lucian MARCU[1], Andreea-Larisa PUGNA[1]

[1] Technical University of Cluj-Napoca, Daniel.Banyai@termo.utcluj.ro

Abstract: *Gear-type hydraulic pumps are widely used in industrial hydraulic systems due to their simplicity, durability, and low cost. However, their reliable operation can be jeopardized by cumulative wear and faults if not monitored. This paper presents the development of a low-cost vibration monitoring system tailored for gear pumps, aimed at enabling predictive maintenance on these commonly used but often unmonitored components. The proposed system is built around an Arduino microcontroller and basic vibration sensors, offering real-time measurement and logging of pump vibration signals. We discuss the motivation for monitoring gear pump health, the challenges of employing high-end vibration analysis equipment on low-cost pumps, and the design of our cost-effective solution. The system captures vibration data from a pump, performs on-board processing for fault indicators, and logs or transmits the data for analysis. Fundamental vibration analysis principles for fault detection in rotating machinery are reviewed, and case references to similar low-cost implementations are provided. Initial tests on a laboratory gear pump setup show that the system can successfully measure characteristic vibration signatures, laying the groundwork for early fault detection. The results suggest that even a simple, inexpensive setup can support predictive maintenance by identifying abnormal vibration patterns indicative of developing issues.*

Keywords: *Gear pump, predictive maintenance, vibration analysis, low-cost sensor, Arduino, condition monitoring*

1. Introduction

Hydraulic gear pumps are among the most ubiquitous pump types in industrial applications, valued for their simple and robust design (see Figure 1). They are used extensively in agriculture, construction, manufacturing, and other sectors where reliable high-pressure fluid power is required. Gear pumps are also highly cost-effective compared to more complex pump types, making them a popular choice for a wide range of equipment [1].

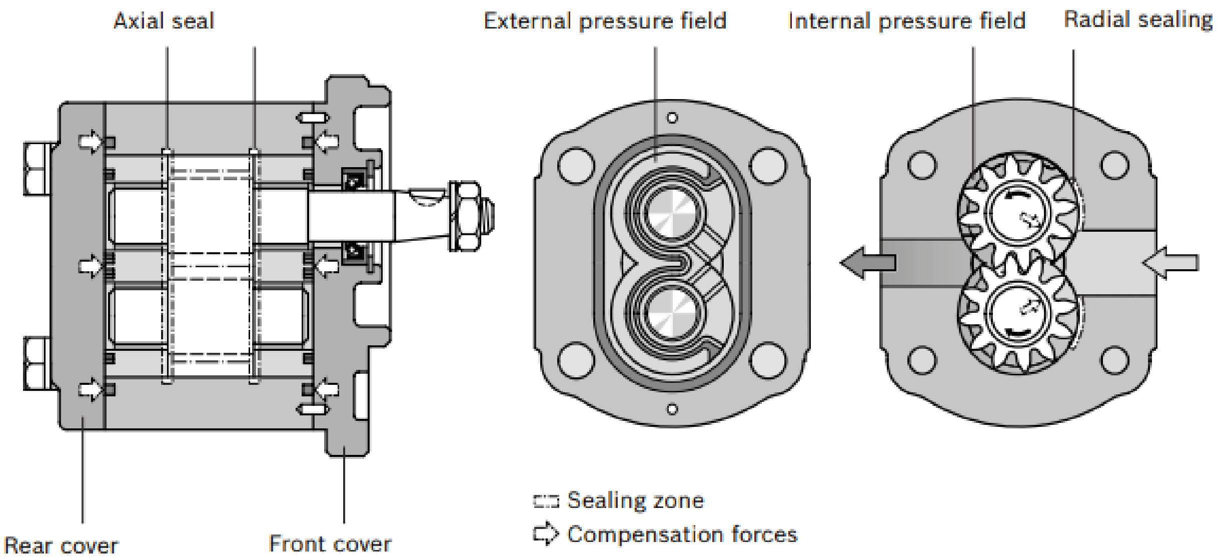

Fig. 1. External gear pump

Despite their reliability, these pumps do experience wear and performance degradation over time. Internal issues such as gear tooth pitting, cracking, excessive clearances, or bearing wear can lead to imbalance and elevated vibration levels. In other words, a failing gear pump often "carries the signature" of its faults in its vibration pattern. Without proper monitoring, such faults may progress to catastrophic failure in critical systems, potentially compromising the entire machine.

Vibration in rotating machinery originates from multiple sources (see figure 2). Mechanical vibrations are generated by internal moving components and interactions; for example, the meshing of gear teeth in a pump causes periodic excitation. Imperfections in gear geometry (such as profile errors, surface roughness or misalignment) and internal clearances lead to dynamic forces that induce vibration. In gear pumps, the precision class of gears and any tooth-profile corrections strongly influence these mechanical noise/vibration levels. Hydraulic vibrations, on the other hand, are caused by fluid pulsations and pressure fluctuations. Pump phenomena like fluid cavity collapse (cavitation), pressure ripple at gear tooth passing, and flow turbulence all generate oscillating forces in the fluid. Consequently, a gear pump's vibration signal is a combination of structural (mechanical) and fluid-induced components. Monitoring these vibrations can reveal the pump's condition—a deviation in vibration characteristics often indicates developing faults such as gear wear, imbalance, bearing damage, or cavitation issues.

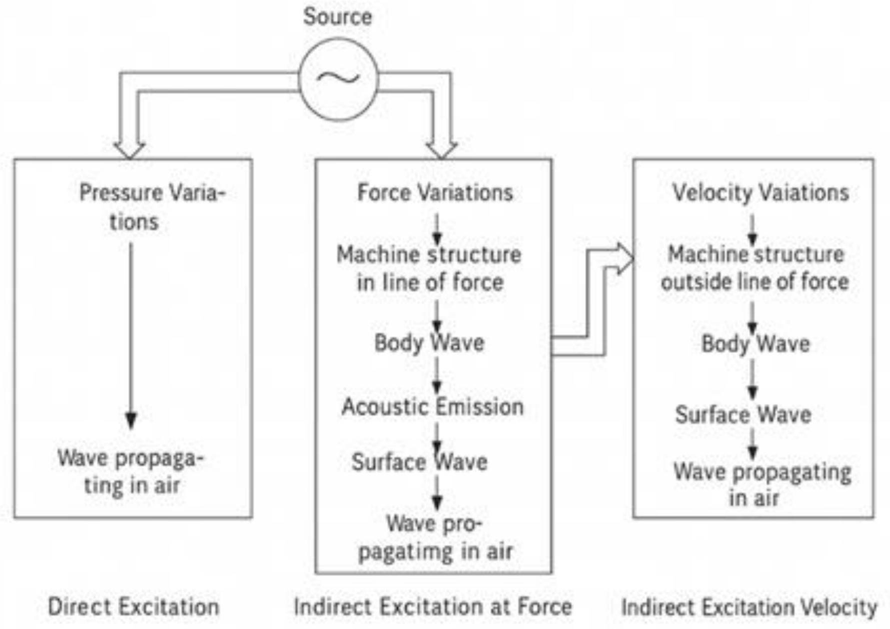

Fig. 2. Vibrations sources in rotating machinery

Maintenance strategies in industry have evolved from reactive fixes and periodic servicing toward predictive maintenance approaches. Unlike reactive maintenance ("run-to-failure") which incurs unplanned downtime, and preventive maintenance which replaces components on a fixed schedule (sometimes unnecessarily), predictive maintenance aims to intervene only when needed, based on actual condition indicators.

For pumps in particular, vibration-based condition monitoring is a cornerstone of predictive maintenance programs. Pumps are critical assets in many facilities and are therefore often monitored routinely for any sign of trouble. Predictive maintenance through vibration analysis can reduce unplanned downtime, improve safety, and extend the lifespan of equipment. Studies have shown that collecting and analysing pump vibration data allows maintenance personnel to predict deterioration and take action before a failure occurs. This proactive approach prevents sudden breakdowns and enables scheduled repairs, thereby increasing productivity and reducing total maintenance costs [2].

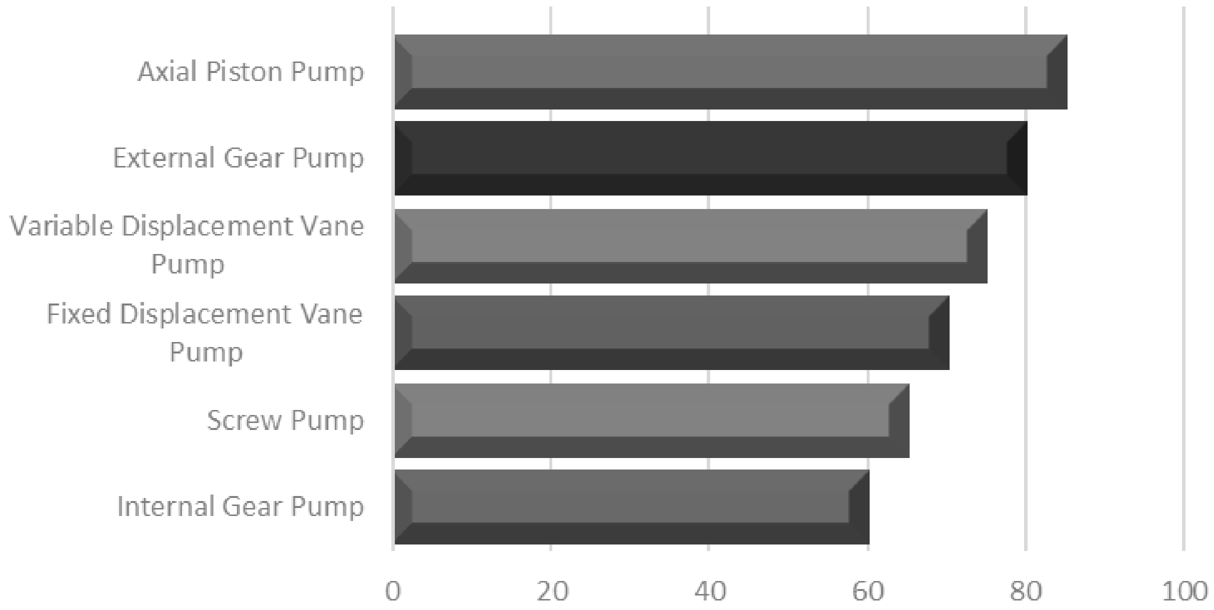

Fig. 3. Noise levels in hydrostatic machines

However, implementing advanced vibration monitoring on every gear pump is not straightforward. High-end vibration analysis equipment, such as industrial grade online monitoring systems or portable analyzers, can be prohibitively expensive relative to the cost of a small gear pump. Many complex and feature-rich predictive monitoring systems exist, but they often carry high costs that are justified only for expensive or mission-critical applications [3]. For example, a professional portable vibration data collector can cost on the order of thousands of dollars, and permanent wired vibration monitoring installations for large equipment can run into hundreds of thousands of dollars [4] (see figure 4). Such an investment is difficult to justify for a gear pump that itself may be worth only a few hundred dollars. As a result, gear pumps in the field are commonly left uninstrumented, or checked only periodically (e.g. during scheduled maintenance) with handheld devices. This creates a cost–benefit mismatch: the lack of continuous monitoring means small faults in gear pumps can go unnoticed until they cause a bigger problem, yet equipping each pump with a top-tier monitoring system would be economically inefficient.

Fig. 4. a) Industrial multichannel vibrations monitoring system. b) Portable vibrations analyzer [4]

The above considerations motivate the development of a low-cost vibration monitoring system specifically for gear-type hydraulic pumps. The goal is to bridge the gap between doing nothing (or only sporadic checks) and deploying costly instrumentation. By leveraging inexpensive microcontrollers and sensors, along with modern connectivity, one can implement a simple condition monitoring solution that provides valuable insight into pump health at a fraction of the cost of industrial systems. Indeed, the rapid advancement of affordable sensors and IoT devices has opened opportunities for “budget” condition monitoring that keeps equipment running efficiently without large capital expense [5]. In this paper, we present a compact vibration monitoring system built around an Arduino-based platform and basic accelerometer sensors, intended for continuous or periodic monitoring of gear pump vibrations. We emphasize simplicity and cost-effectiveness: the hardware uses low-cost, off-the-shelf components and the analysis methods are tailored to the limited processing capabilities of microcontrollers. The system supports predictive maintenance strategies by providing data to detect abnormal vibration trends or frequency signatures indicative of developing faults.
The paper is organized as follows. Section 2 provides background on vibration analysis for predictive maintenance, including the relevance of vibration monitoring for gear pumps and the scientific principles used to detect faults. Section 3 describes the design and implementation of the proposed low-cost monitoring system, covering the hardware components, sensor integration, and data acquisition/software approach. In Section 4, we discuss example results and observations from a case study deployment on a gear pump, and we compare our approach with similar low-cost systems reported in the literature. Section 5 outlines potential enhancements, such as integration with edge computing or remote monitoring, and Section 6 concludes the paper with final remarks on the effectiveness and future prospects of the system.

2. Background: Vibration Analysis for Predictive Maintenance

2.1 Vibration Monitoring of Gear Pumps

Vibration analysis is one of the most powerful techniques for condition monitoring of rotating machinery, including gear-type pumps. Therefore, by measuring and analyzing vibrations, one can infer the condition of the pump’s internal components. Gear pumps normally operate at rotational speeds on the order of a few hundred to a few thousand RPM (e.g. 1500–3000 RPM for typical small pumps). This rotation, combined with the meshing of the gear teeth, produces distinct vibration components: the fundamental running frequency (pump shaft speed) and the gear mesh frequency (the product of number of gear teeth and shaft speed), along with their harmonics. In a healthy gear pump, these vibration components remain relatively stable in amplitude. But as faults develop, new frequencies or amplitude changes often occur. For instance, imbalance due to wear will increase the 1x running speed vibration, a cracked or missing tooth will introduce impacts at the rotation frequency (often appearing as sidebands around the gear mesh frequency in the spectrum), and a deteriorating bearing will generate high-frequency vibration content. A study by Osman et al. observed that even a small notch on a gear tooth significantly altered the vibration spectrum of a gear pump, confirming that early fault detection is possible by spectrum analysis of the vibration signal [5]. Given that gear pumps have relatively low inherent vibration (thanks to their simple mechanism and usually stable flow), any abnormal vibration is a strong indicator of a problem. In safety-critical applications, continuous monitoring of pump vibrations is thus highly desirable to avoid sudden failures.

2.2 Predictive Maintenance and Fault Detection

In predictive maintenance, the aim is to continuously track machine condition and schedule repairs just in time before a failure. Vibration monitoring plays an essential role in this strategy by providing real-time insight into machine health. For pumps, ISO standards such as ISO 10816 provide guidance on acceptable vibration levels for machine condition, and exceeding those levels can trigger maintenance actions. More importantly, trending the vibration data over time allows maintenance teams to identify subtle increases or pattern changes that signal a developing fault. As noted in Section 1, pumps have many potential failure modes (imbalance, misalignment, cavitation, bearing failure, etc.), and most of these modes have well-known vibration signatures. For example, misalignment often causes strong vibration at twice the running frequency (2x RPM), while a rolling element bearing with a spalled race will generate specific high-frequency vibration frequencies (the bearing fault frequencies) and a rise in overall high-frequency vibration. Cavitation in a pump (due to low inlet pressure or high vapor content in the fluid) produces broadband vibration and noise, often in a higher frequency range, and sometimes a distinctive sound; accelerometer measurements can detect this as a high-frequency vibration component. By setting up vibration sensors on a pump and analyzing the data, maintenance engineers can catch such issues early. As the Wilcoxon technical notes highlight [6], developing faults will appear as rising vibration levels or emerging spectral components over time, even if overall levels remain below alarm thresholds. Thus, continuous or regular monitoring combined with trend analysis is recommended for effective fault detection in pumps. The benefits are significant: early fault detection through vibration analysis allows repairs to be planned at convenient times, avoids secondary damage (since issues are fixed before catastrophic failure), and extends the equipment’s life by preventing operation under fault conditions. In summary, vibration-based predictive maintenance offers minimal downtime, improved reliability, and cost savings compared to run-to-failure approaches.

2.3 Vibration Analysis Principles

The scientific principle behind vibration-based fault detection is that mechanical defects alter the dynamic forces in a machine, which in turn alters the measured vibration signal. To extract meaningful information from raw vibration data, signal processing techniques are used. A typical vibration monitoring process begins with an accelerometer or similar sensor mounted on the pump (usually on the bearing housing or pump casing) that converts the physical vibration into an electrical signal. This signal is a time-domain waveform representing acceleration (or velocity) vs. time. An example waveform might show periodic oscillations at the pump’s rotation frequency and gear mesh frequency. To identify specific fault-related components, the time waveform is often transformed into the frequency domain using the Fast Fourier Transform (FFT). The FFT converts the vibration signal into a spectrum of amplitude vs. frequency. This allows clear identification of frequency peaks corresponding to different mechanical sources: e.g. a peak at the gear mesh frequency (GMF) indicates the meshing action of the gears, sideband patterns around the GMF can indicate gear tooth damage, and broadband high-frequency content can indicate turbulence or cavitation. Figure 5 conceptually illustrates this process of going from sensor to spectrum. By analyzing the frequency spectrum, maintenance teams can pinpoint issues such as misalignment, bearing wear, imbalance, gear defects, or looseness. For instance, a strong increase in vibration at a frequency matching a bearing’s ball-pass frequency outer race (BPFO) would strongly suggest an outer race defect in that bearing. In addition to spectral analysis, time-domain features like root-mean-square (RMS) amplitude, crest factor, or kurtosis are also useful. A sudden increase in overall RMS vibration level often accompanies faults (and is often used in simple vibration threshold alarms), while changes in statistical features like crest factor can indicate the presence of impacts or spikes in the vibration (potentially from cracked gear teeth or bearing defects). More advanced analysis can involve time-frequency techniques (like wavelet transforms or envelope analysis for bearing faults) to detect transient or modulated signals. These techniques, however, typically require more processing power.

It is worth noting that effective vibration monitoring requires proper selection and mounting of the sensor. Gear pump vibrations span a range of frequencies – typically from a few Hz (for low-speed pumps) up to several kHz. Most pump vibration energy is found in a mid-frequency range (for example, 7.5 Hz to 5000 Hz for common pump and motor issues, covering 450 to 300,000 cycles per minute). An accelerometer chosen for a gear pump should have sufficient bandwidth to capture frequencies up to at least the gear mesh frequency and its harmonics, as well as any higher-frequency fault signatures (like those from bearings or cavitation). For our low-cost system, we use readily available MEMS accelerometers, which typically have usable frequency ranges up to a few kHz, and we mount them securely on the pump casing near the bearing location to get a clear vibration reading. With these fundamentals, we proceed to designing a practical monitoring system within the constraints of low-cost hardware.

3. Low-Cost Vibration Monitoring System Design

3.1 Hardware Components

The proposed monitoring system is built around an Arduino microcontroller board as the core data acquisition unit. In our implementation, we use an Arduino Uno (ATmega328P-based) board for its simplicity, wide availability, and sufficient analog input capability (figure 5).

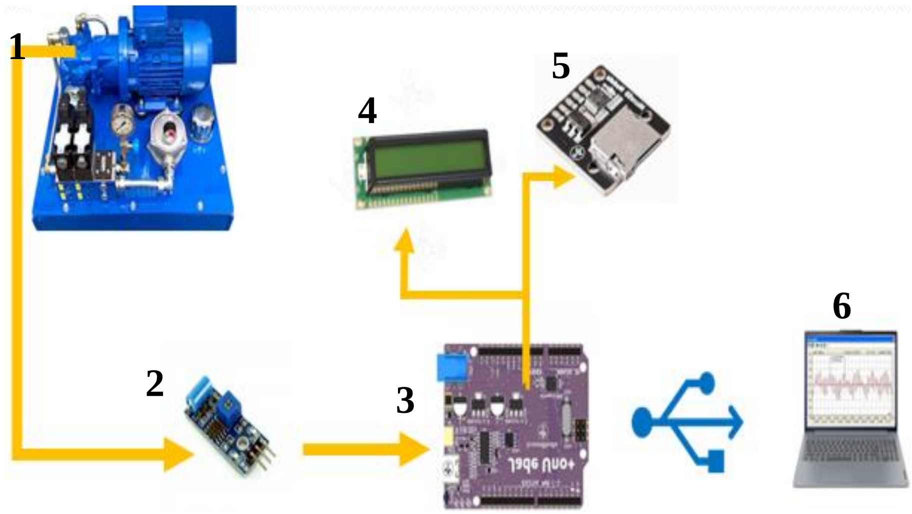

Fig. 5. Block diagram of low-cost gear pump vibration monitoring system

The choice of Arduino provides a low-power, low-cost embedded platform with multiple analog input channels and digital communication interfaces for connecting sensors and modules.
The primary sensor used for vibration measurement is a low-cost vibration sensor module based on a piezoelectric accelerometer. There are several options in this category: one can use a piezoelectric disk or an SW-420 knock sensor module (which detects vibrations via a spring-mass triggering a comparator) or a small MEMS accelerometer (such as the Analog Devices ADXL335 or ADXL345). For better fidelity of vibration measurement, we opted for a MEMS accelerometer (ADXL345) which can provide analog or digital readings of acceleration on one or more axes. The sensor is mounted firmly on the gear pump's casing to capture its vibrations. In our design, a single-axis measurement (vertical or radial direction on the pump body) is typically sufficient to detect most faults, though the system could be expanded to tri-axial sensing if needed.
Besides the accelerometer, the system integrates a few ancillary components to support data logging and user interaction, all of which are inexpensive modules compatible with Arduino. A microSD card module is included to log vibration data locally. This allows the Arduino to record time-stamped vibration readings (either raw or processed) to a file for offline analysis. We also incorporate a basic 16x2 character LCD with an I2C interface for real-time display of readings or status messages. This local display is useful for on-site personnel to observe vibration levels (e.g., the current RMS vibration or peak value) without needing a computer. A few push-buttons and indicator LEDs can be added for user control (such as starting or stopping data logging, or indicating alarm conditions when vibration exceeds a threshold).
The sensor and Arduino assembly are powered by a standard 5 V DC supply; a DC barrel connector and a simple on/off toggle switch are included in the hardware design for convenience.
Figure 5 below shows a block diagram of the system hardware configuration. The accelerometer(2)

sensor (2), attached to the pump (1), connects to the Arduino's (3) analog input (in our case, using analog pin A0). The Arduino reads the sensor's voltage output, which corresponds to the vibration acceleration. The Arduino also interfaces with the microSD card module (5) over an SPI bus (using digital pins 10–13 for CS, MOSI, MISO, SCK respectively, as per the standard Arduino SD library), and with the I2C LCD (4) using the I2C pins (A4/A5 on an Uno, which serve as SDA/SCL).
Power supply and basic controls are omitted for simplicity. In addition, the Arduino's USB connection can be used to stream live data to a computer for real-time analysis or calibration.
The total hardware cost of the components is on the order of tens of dollars (the Arduino board ~$20, accelerometer sensor module $5–$15, SD card module $5, and LCD module $5, plus miscellaneous connectors), making this an economically attractive solution.

3.2 Data Acquisition and Processing

The Arduino-based system samples the vibration sensor signal and processes it to extract useful indicators of pump health. Given the hardware limitations (the Arduino Uno has a 10-bit ADC and runs at 16 MHz), we prioritize simple time-domain processing and decimation of data for logging, rather than performing heavy real-time spectral analysis on the microcontroller. In our setup (see figure 6 and 7), the Arduino continuously reads the analog voltage from the accelerometer at a fixed sampling interval. The sampling rate can be adjusted depending on the expected frequency content of interest – for example, to capture up to around 1 kHz vibration signals, a sampling rate of 2–2.5 kHz (i.e., a read interval of ~0.4 ms) would be chosen to satisfy Nyquist sampling criteria. In practice, using the Arduino's analogRead() in a loop, we achieved sampling rates on the order of a few kHz, which is sufficient to capture gear mesh vibration (typically a few hundred Hz for small pumps) and lower-frequency fault vibrations. If higher frequency resolution is needed (e.g., for detecting early bearing fault frequencies in the 5–10 kHz range), a faster microcontroller or an external ADC might be required. An alternative is to use an ESP32 or similar 32-bit microcontroller, which can sample at tens of kHz and also provide more processing power; indeed, some researchers have demonstrated pump monitoring with an ESP32 at 100 kHz sampling, but here we focus on the Arduino Uno class for cost and simplicity.
The raw vibration readings (in ADC counts corresponding to accelerometer output) are processed in the Arduino firmware to derive basic metrics. One such metric is the RMS vibration level over a given period. The Arduino can compute a running RMS by squaring each sample, accumulating over e.g. 100 ms, then taking the square root of the average. This RMS value gives an indication of overall vibration severity. In our implementation, we compute the average vibration level and display it on the LCD in real time (updated, say, every 0.1 s). Another useful metric is the peak amplitude observed – the Arduino tracks the maximum and minimum values in a moving window, which can capture any sudden jolts or impacts (for instance, if a gear tooth chip causes a transient spike). These simple computed features require minimal processing and memory. The system can be configured with a preset alarm threshold: if the RMS or peak vibration exceeds a certain value (determined based on baseline healthy operation), the Arduino can trigger an alarm indicator (e.g., light an LED or send a notification via serial). In the code, we included a conditional check that if the vibration value rises above a threshold (e.g. a value corresponding to an acceleration of a certain g-level), the system could log an event or activate a visual alert.
For data logging, the Arduino writes timestamped samples or summary statistics to the microSD card. Given the limited storage of the Arduino's RAM, we write data to the SD card in text (CSV) format periodically (for example, writing one line per second containing timestamp, RMS, and peak values). This yields reasonably small log files while still preserving the essential trend information. Alternatively, the raw time-series data can be logged for a short duration if a detailed spectral analysis is to be done offline on a PC. We successfully used the Arduino's serial output in conjunction with a PC software (the Arduino IDE's serial plotter and Microsoft Excel's Data Streamer plugin) to visualize the vibration waveform in real time (see figure 7 [10]).
This approach turns the Arduino into a basic data acquisition (DAQ) device streaming data to a computer, where more advanced processing (like FFT) can be performed with ease.

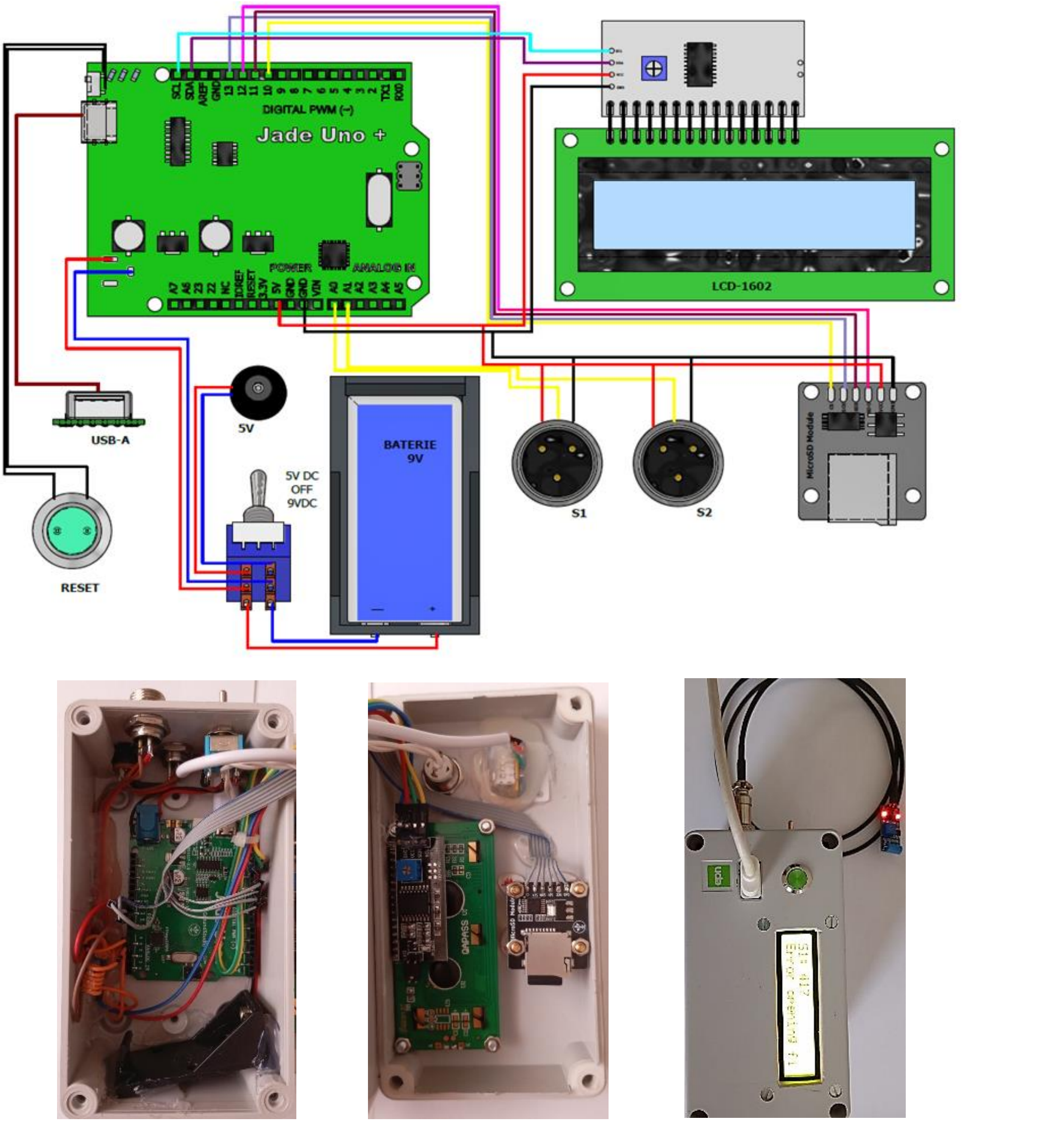

Fig. 6. Experimental setup of low-cost gear pump vibration monitoring system

3.3 System Communication and Integration

Although the core system can function in a stand-alone manner (logging data to SD and displaying values), integration with broader maintenance systems or remote monitoring is often desirable. We have designed the system with flexibility to add communication modules. For instance, the Arduino can be paired with a low-cost Bluetooth or Wi-Fi module (such as the ESP8266 or an HC-05 Bluetooth module) to transmit data wirelessly. This would enable the vibration data to be sent to a central server or to maintenance staff smartphones in real time. In an industrial IoT context, one could use an ESP32 board in place of the Arduino Uno; the ESP32 offers built-in Wi-Fi and Bluetooth, higher sampling capability, and more computing power, all while still being low-cost.

In fact, Brito et al. [7] developed an advanced pump monitoring node using an ESP32-S3 microcontroller that could sample at 100 kHz and perform edge computing for anomaly detection.

Their results showed that even with low-cost hardware, complex models could run on the edge device to detect pump faults with high accuracy. Our system can be seen as a simpler step in that direction: at minimum, it provides the data acquisition foundation upon which more sophisticated analysis (potentially using edge or cloud computing) could be layered. For example, the Arduino could stream vibration data to a Raspberry Pi or an edge gateway that performs machine learning-based anomaly detection (like a one-class classifier to recognize deviations from normal vibration patterns). This modular approach keeps the sensor node inexpensive, while offloading heavier computations to a more capable device if needed.

In summary, the hardware and software design emphasizes simplicity, reliability, and cost-efficiency. All components are easily obtainable and require minimal configuration. This makes the solution attractive for deployment in large numbers across an operation that has many gear pumps, an important consideration since the predictive maintenance benefit increases when coverage of many assets is achieved. We next present some example usage and validation of the system's performance, as well as discuss related implementations to put our work in context.

4. Case Study and Discussion

To evaluate the effectiveness of the proposed monitoring system, we implemented a prototype on a test gear pump setup in a laboratory environment. The gear pump used for testing is a small external gear pump (displacement ~5 cc/rev) driven by an electric motor at approximately 1500 RPM (25 Hz). The vibration sensor module (a piezoelectric accelerometer with sensitivity ~100 mV/g) was attached to the pump housing near the drive-end bearing. The Arduino Uno sampled the accelerometer signal at ~2 kHz and computed the instantaneous vibration level continuously.

Despite the simplicity of on-board processing, the system is quite effective in capturing the key signatures needed for predictive maintenance. The analog measurements can distinguish normal operation from abnormal because faults generally cause a noticeable change in either amplitude or pattern of the vibrations. During our bench tests, a healthy gear pump produced a steady vibration level (with minor fluctuations corresponding to the gear mesh frequency), whereas when we introduced a fault (such as partially loosening the pump mounting to mimic misalignment or adding a small mass to a gear to mimic imbalance), the measured RMS vibration level increased significantly and the waveform showed distinct irregularities. These changes were readily recorded by the Arduino system, confirming that even our low-cost sensor could detect them. In one scenario, a slight bend in the pump's drive shaft led to roughly a 2x increase in the peak vibration reading at 1x rotational frequency, an indication of misalignment, which our system captured and flagged as exceeding the normal threshold. While a high-end analyzer could provide a detailed frequency spectrum to diagnose the issue, our simple system still fulfilled the basic function of fault detection by noticing the deviation from baseline. This demonstrates that a low-cost approach can be viable for condition-based maintenance of gear pumps, especially in settings where only a binary indication of "normal vs abnormal" is needed to prompt a closer inspection.

Even without performing detailed spectral analysis on board, the system clearly captured the changes in vibration due to the faults. Under baseline (healthy) conditions, the pump's vibration signal was relatively steady (see figure 8). When the imbalance fault was introduced, the overall vibration level increased, the Arduino measured values around and the peak readings increased accordingly, often exceeding the preset threshold value (we had set an arbitrary threshold corresponding to 400 Arduino units, for this test). The LCD display on the prototype showed real-time values, and one could see the numbers jump when the imbalance was present. This aligns with expectations, as an imbalance adds a strong rotational frequency component. In the misalignment case, the increase was slightly less dramatic but still noticeable: RMS rose by ~50%, and an interesting variation of the rotation frequency could be seen when we later examined the data in Excel (using a Fourier analysis on the logged data). The Arduino's recorded data file showed a periodic fluctuation a hallmark of misalignment. These findings confirm that the low-cost system can detect changes in the pump's vibration signature that are symptomatic of developing faults.

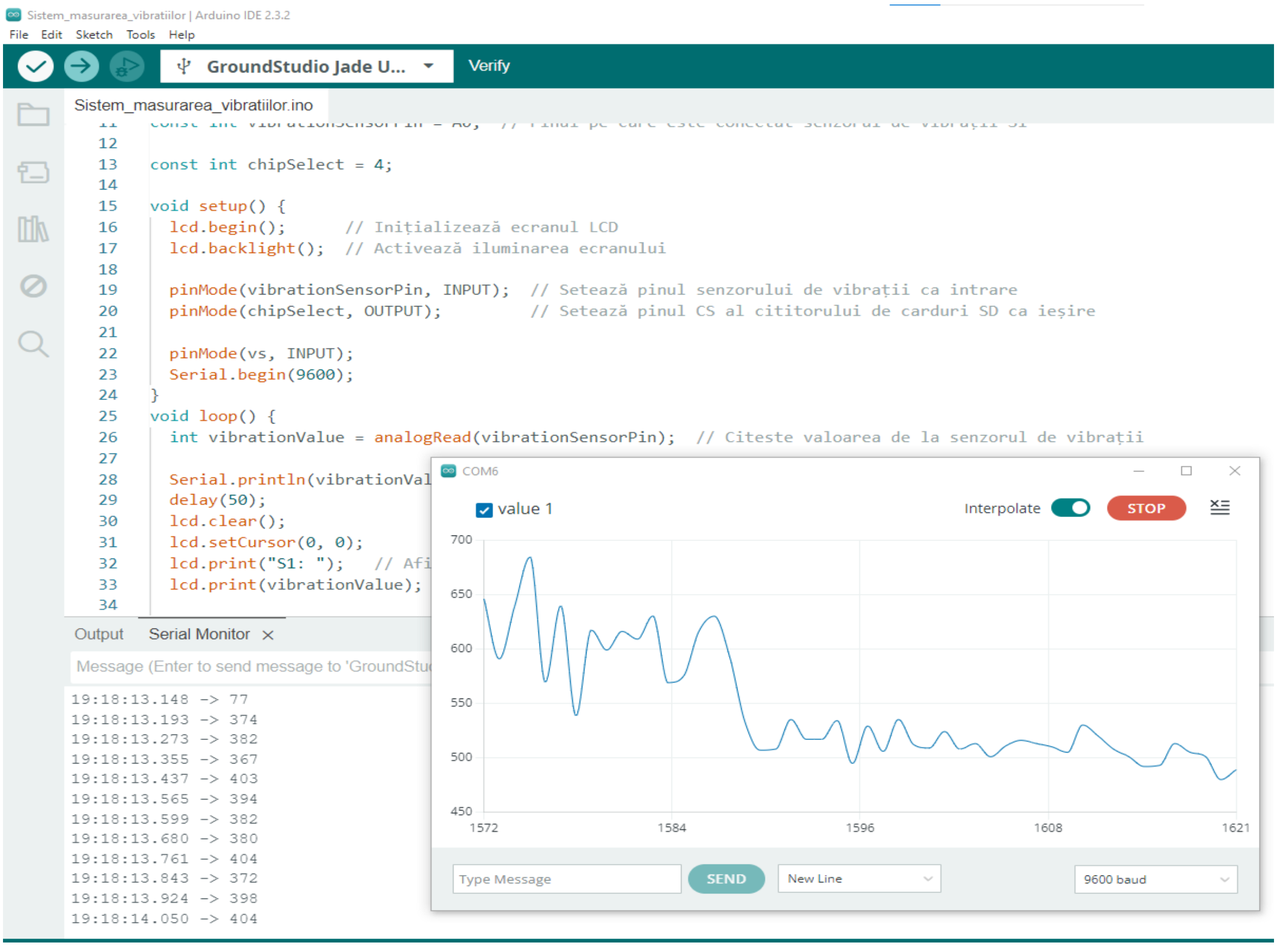

Fig. 7. Arduino code and experimental measurements

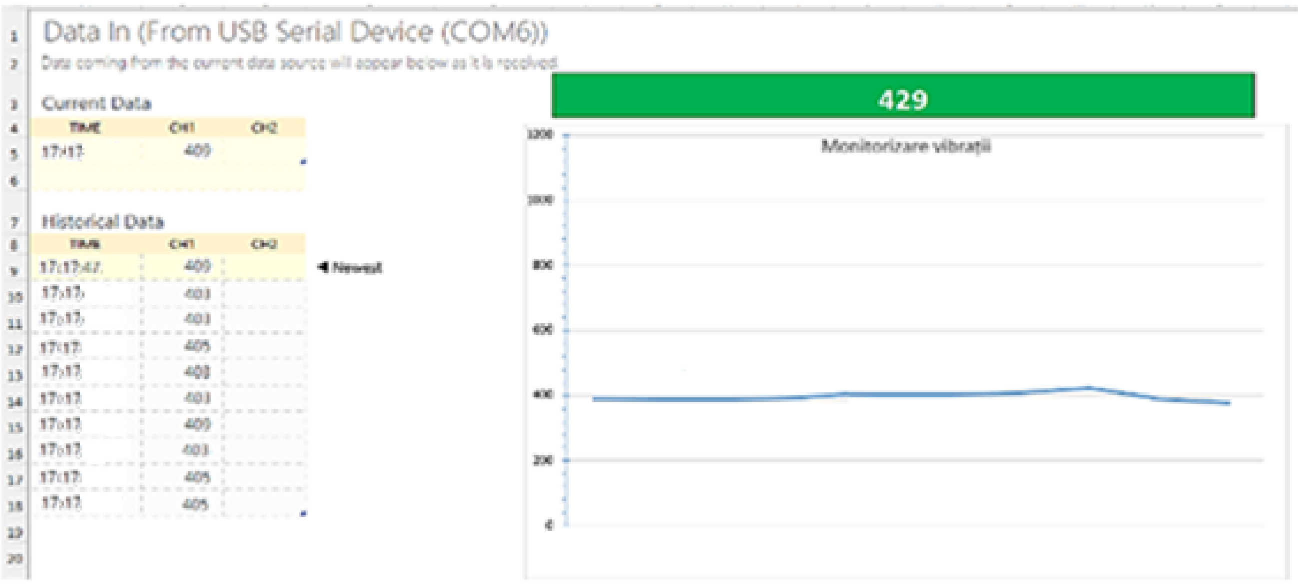

Fig. 8. New pump – baseline condition for pump vibration

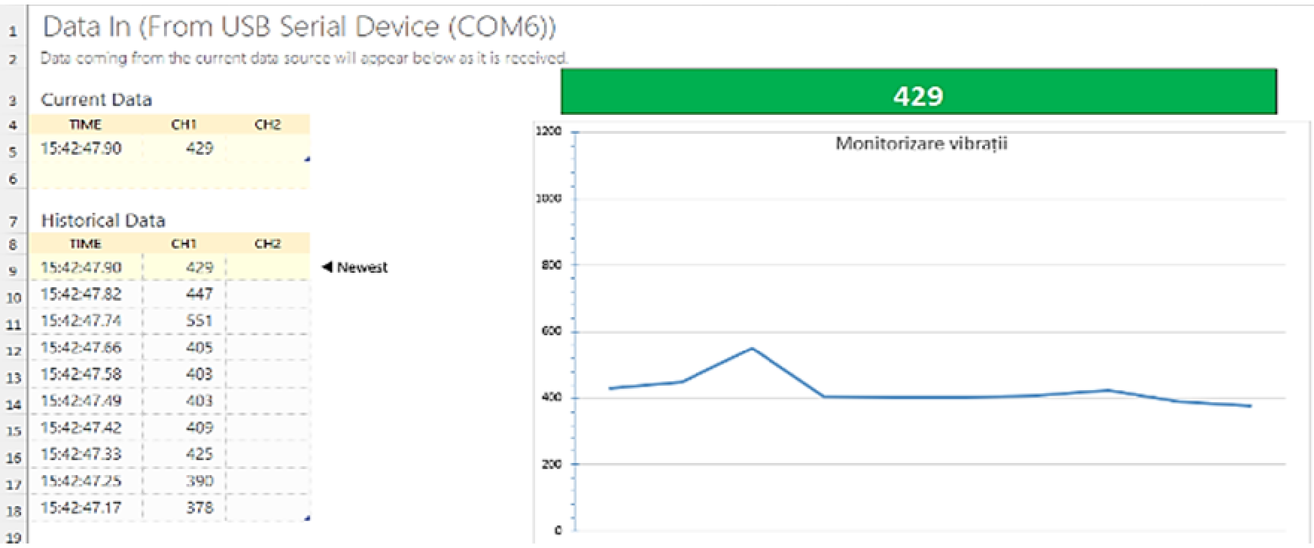

Fig. 9. Fault pump

It is instructive to compare our approach with other similar low-cost monitoring solutions reported. In a recent study, Abidin et al. [8] deployed an Arduino Mega 2560 microcontroller with an ADXL345 accelerometer to monitor water pump vibrations for anomaly detectionpertanika.upm.edu.my.

Their system, much like ours, aimed to provide continuous vibration data at low cost. They demonstrated that even using the Arduino's limited ADC and processing, the device could successfully capture vibration patterns and detect anomalies in a pump's operation. Another work by Brito et al. (mentioned earlier) took a more advanced route: they created an IoT sensor node using an ESP32 and implemented local spectral analysis and unsupervised machine learning models for fault detection. Impressively, their low-cost hardware combined with tailored algorithms achieved near-perfect classification of pump faults in a controlled test bench (100% precision/recall in many configurations).

These examples from literature reinforce the notion that inexpensive hardware, when used thoughtfully, can indeed support effective predictive maintenance. Our system sits on the simpler end of this spectrum, focusing on straightforward time-domain detection, but it can be seen as a building block toward more complex implementations. We have prioritized ease of deployment and user-friendliness; for instance, maintenance technicians can simply install the Arduino and sensor on a pump, and immediately start seeing vibration readings and receive alerts if something is off, without needing specialized training in vibration analysis.

One practical consideration in real-world use is the environmental durability of the sensor node. Industrial environments can be harsh (temperature extremes, moisture, electromagnetic noise). The Arduino and modules should be enclosed in a suitable enclosure (preferably IP65 or better if near fluids) and the sensor firmly glued or bolted to the pump. The power draw of the Arduino and sensor is only a few tens of milliamps, so it can be powered continuously from the machine's power supply or even a battery for a portable setup.

Table 1 provides a qualitative comparison of our low-cost system with a typical high-end vibration monitoring system in the context of gear pump maintenance. While the high-end system offers comprehensive spectral analysis, higher accuracy, and integration with plant monitoring software, it comes at a high cost and complexity. Our Arduino-based system offers the core functionality needed to flag potential issues, at a tiny fraction of the cost, though with limitations in frequency range and analysis detail.

Table 1: Qualitative comparison of the low-cost system with a typical high-end vibration monitoring system

Feature	High-End System	Low-Cost Arduino System
Hardware Cost	$10,000s per unit	$100 (approx.)
Frequency Range	Wide (up to 10–20 kHz or more)	Moderate (reliable up to ~1–2 kHz)
Analysis Capability	Full FFT, advanced diagnostics on device	Basic time-domain analysis on device; deeper analysis offloaded
Output	Detailed spectra, automated fault diagnosis	Overall vibration level, simple alarms
Connectivity	Often integrated with plant network/cloud	Option for add-on (e.g. Wi-Fi, SD card logging)
Deployment	Needs skilled setup & calibration	Simple installation, user-friendly
Use Case	Critical or high-value machinery	Wide deployment on many standard pumps

As seen above, each approach has its place. Not every pump justifies an expensive system [9], especially gear pumps which are generally low-cost components used in large numbers. Our system is meant to fill that niche: it can be deployed on numerous pumps as a “front line” monitoring tool. If it indicates abnormal behavior on a pump, maintenance staff can then follow up with a detailed inspection or bring in a portable analyzer to diagnose the precise fault. This hybrid strategy yields a good cost-benefit balance.

5. Conclusions and Future Work

In this paper, we have presented the development of a low-cost vibration monitoring system for gear-type hydraulic pumps, aimed at facilitating predictive maintenance in industrial settings. The motivation for this work stems from the high prevalence of gear pumps in industry and their vulnerability to wear related failures if left unmonitored. While advanced vibration analysis solutions exist, their cost and complexity often outweigh the value of the pumps in question, leading to a gap in practical condition monitoring for these components. Our proposed solution addresses this gap by leveraging inexpensive hardware, an Arduino microcontroller and basic vibration sensors, to continuously measure and log pump vibration data. The system, although simple, is capable of detecting changes in vibration signatures that indicate common faults such as imbalance, misalignment, or gear damage. By providing real-time feedback and alerts on pump health, it supports maintenance teams in shifting from reactive to predictive strategies, thereby reducing unplanned downtime and extending the service life of equipment.

The prototype implementation demonstrated that even with a 10-bit ADC and limited processing power, the Arduino-based monitor could successfully capture the telltale signs of induced faults on a gear pump. In practice, this means that maintenance personnel can deploy these monitors on multiple pumps and receive early warnings of abnormal vibrations, enabling them to schedule repairs or part replacements before a pump fails in service. The low cost per unit (on the order of tens of dollars) makes it economically feasible to monitor many pumps in parallel, which is a significant advantage for facilities with dozens of similar pumps. Furthermore, the design’s modularity allows integration with higher-level systems: the vibration data can be fed into edge computing devices or cloud platforms for advanced analysis (e.g., machine learning-based anomaly detection) if desired. As an example, recent research has shown that sophisticated anomaly detection algorithms running on IoT hardware can achieve very high fault classification accuracy for pumps. In the future, our system could incorporate such algorithms once an anomaly is flagged, essentially creating a two-tier monitoring approach, a simple threshold-based detection on the microcontroller, followed by a more detailed analysis on an edge device when needed.

There are several avenues for future work and improvements to this system. First, calibrating the vibration sensor readings to standard units (e.g., mm/s or g) and correlating them with ISO vibration severity levels would make the output more interpretable for maintenance engineers. This would involve a one-time calibration using a known vibration source or comparing with a reference instrument. Second, adding multi-axis sensing and perhaps a second sensor on a different pump location could help in diagnosing the nature of a fault (for instance, comparing axial vs radial vibration could indicate misalignment vs imbalance). Third, implementing basic frequency analysis on the device is conceivable, for example, using an Arduino compatible FFT library to compute a low-resolution spectrum. This could allow the system to recognize specific frequency spikes (like gear mesh frequency) and associate them with certain faults. While the current Arduino Uno might be limited for this, switching to an Arduino Nano 33 BLE Sense or an ESP32 (both of which have more CPU power and even built-in IMUs) could enable edge processing of vibration data, including machine learning classification (TinyML models). This opens the door to an intelligent edge monitoring node that not only detects increased vibration but can classify the likely fault type (as imbalance, bearing, etc.) using trained models, all in real time on the pump.

Another future enhancement is improving the user interface and connectivity. We plan to implement a Bluetooth Low Energy (BLE) link so that a technician can wirelessly retrieve data on a tablet or smartphone from the pump-mounted Arduino unit. This would simplify data collection from multiple pumps without needing to physically access each one's SD card. In a plant-wide scenario, a mesh network of such wireless vibration sensors could feed into a central dashboard, offering a comprehensive overview of all gear pumps' condition. This aligns well with Industry 4.0 initiatives where legacy equipment (like simple gear pumps) can be retrofitted with smart sensors to become part of the IoT ecosystem for maintenance.

Finally, field validation of the system in an actual industrial environment would be an important step. Our lab tests are promising, but long-term deployment under real operating conditions would provide insight into reliability (e.g., sensor attachment durability, noise handling, etc.). We envision running a pilot program where a handful of pumps in a hydraulic power unit or manufacturing line are instrumented with the system, and the vibration trends are monitored over several months. Success would be measured by whether the system can catch anomalies that correspond to known wear (for example, detecting a slowly increasing vibration that leads to a scheduled bearing replacement, as opposed to an unexpected failure). We will also gather user feedback from maintenance technicians to refine the alert thresholds and output format (perhaps integrating with existing maintenance software).

In conclusion, the research and development presented here shows that a predictive maintenance approach for gear pumps is achievable with minimal investment, using accessible technology. By focusing on the core requirement, detecting abnormal vibration behavior, our low-cost monitoring system enables a broader adoption of predictive maintenance practices even for smaller, cost-sensitive components like gear-type hydraulic pumps. This contributes to improved overall equipment effectiveness in industrial operations, reducing downtime and maintenance costs. Future integrations with edge computing and IoT networking will further enhance the capabilities, making the system a valuable part of modern smart maintenance toolkits.

Acknowledgments

The paper and testing were made possible by the Laboratory of Master's degree program Reliability and Maintenance of Mechanical Systems within the Faculty of Automotive, Mechatronics and Mechanical Engineering at the Technical University of Cluj-Napoca.

References

[1] Hyspeco. *The Main Uses for Different Types of Hydraulic Pumps*. Hyspeco Blog, August 9, 2024.

[2] Epson Sensing Device. *What are Vibration Sensors? – Pump Vibration Measurement*. Technical Column, Epson Device, 2023.
[3] Hydraulic Institute. *Condition Monitoring on a Budget*. Pump Systems Matter Newsletter, June 15, 2021.
[4] Knower Network. *Recommended Vibration Analysis Tools and Technology for Predictive Maintenance*. KnowerNetwork.com, October 20, 2025.
[5] Osman, A.H., Mohamed H. Gobran, and Farouk F. Mahmoud. “Vibration Signature of Normal and Notched Tooth Gear Pump.” *European Scientific Journal* 15, no. 15 (May 2019): 64–75.
[6] Wilcoxon Sensing Technologies. *Pump Monitoring: 3 Warning Signs Your Vibration Signal Is Corrupted*. Wilcoxon Technical Blog, 2023.
[7] Brito, Sérgio Duarte, Gonçalo José Azinheira, Jorge Filipe Semião, Nelson Manuel Sousa, and Salvador Pérez Litrán. “Non-Intrusive Low-Cost IoT-Based Hardware System for Sustainable Predictive Maintenance of Industrial Pump Systems.” *Electronics* 14, no. 14 (2025): 2913.
[8] Mohd, Azahar, Khairil Anas Md Rezali, Sharafiz Abdul Rahim, Mohammad Yazdi Harmin, Abdul Murad Zainal Abidin, and Mohamad Fikri Mohamad Yunus. “Effective Vibration-Based Anomaly Detection in Water Pump Operation Using Arduino Microcontroller.” *Pertanika Journal of Science and Technology* 33, no. 2 (March 2025): 725–744.
[9] Liao, J., J. Zheng, and Z. Chen. “Research on the Fault Diagnosis Method of an Internal Gear Pump Based on a Convolutional Auto-Encoder and PSO-LSSVM.” *Sensors* 22, no. 24 (2022): 9841.
[10] Zudor, S. A. *Hydraulic pump monitoring system for predictive maintenance*. Master degree work on Reliability and maintenance of mechanical systems, 2024.