CHECKING THE RELIABILITY OF PUMP UNITS BASED ON VIBRODIAGNOSTIC INDICATORS

(considering the issue of modeling the cavitation process that occurs in centrifugal pumps)

"TIIAME" NRU
Adilov Ozodbek Komiljon o'g'li
doctor of technical sciences

Professor Ergashev Rustam Rakhimovich

Abstract:
A numerical analysis of the influence of the geometry of a motor centrifugal pump on the formation of a cavitation cavity in the interblade space of its impeller is presented. A design has been developed for the impeller of a motor centrifugal pump with characteristics similar to this type of device.
A geometric model has been constructed that has compact dimensions, has a correct pressure distribution in the section of the impeller, and is not subject to cavitation at a given operating mode. It is shown that with a relative increase in the outer radius of the impeller or a decrease in its width within 12– 50% in comparison with a model close to that required for stable operation, cavitation occurs at the leading edge of the blade with subsequent growth throughout the entire volume of the flow part of the pump. A pump of this kind can be used as a hydrodynamic machine for the intensification of many chemical engineering processes due to the cavitation effect already at the stage of pumping liquid.

Keywords: cavitation, cavern, computer simulation, ANSYS CFX, centrifugal pump, Predictive Maintenance; CWT; PARAFAC; IPSO; SVM; Diagnostic Technologies; Industrial Efficiency; Agricultural Productivity; Smart Sensors; Data Analysis; Maintenance Cost Reduction; Operational Resilience.

Introduction

The reliability of aircraft engine power plants is largely determined by the functioning of the fuel supply and control systems. One of the most critical components of these systems is the pump units. There are numerous cases of failures and accidents of aircraft equipment due to the failure of these units. This problem is most acute for forced power plants operating in harsh operating conditions. Pump units are among the most heavily loaded elements of power plants, while the stresses in the pumping units of the pumps are comparable only with the stresses of the most heavily loaded elements of the engines. As a result, the service life of the pumps is usually 2-3 times lower than the service life of the power plants themselves, the value of which, as a rule, is from 15 to 20 thousand engine hours. Fuel pumps of modern afterburning engines installed on high-altitude aircraft (primarily strategic and long-range aviation) experience significant dynamic loads. This is due to the fact that they are usually made in combination (including auger centrifugal (SC) - booster and oscillating main - gear stage (GS) and are subject to intense latent cavitation processes. The presence of the latter is associated with the multi-mode pumping stages, providing a wide range of flow rates in the main and afterburner combustion chambers of the engine. A distinctive feature of the considered fuel supply systems of aircraft engines with combined pump units is that both in afterburner and non-afterburner operating modes, all fuel consumed by the engine is pumped through the auger-centrifugal stage of the specified pumps. This leads to the operation of the auger-centrifugal stage in non-design modes and to the intensification of cavitation processes, often latent in nature. Such hidden cavitation, without leading to a pressure breakdown, causes significant dynamic and vibroacoustic loading of the pump elements As is known, a distinctive feature of the fuel supply systems of aircraft engines is the presence of a large number of functionally connected hydromechanical elements and units, each of which can serve as a source of vibrations or increased noise, and their mutual influence can cause self-oscillations in the system. The complex structure of aircraft fuel system units, the many factors affecting their operation, also determines many reasons causing non-stationarity of processes in the system.

The problem of increased vibration loading of pump unit elements has recently become relevant for combined pumps of gas turbine engines.

Background and Context

Cavitation is widely used to clean the surfaces of machines and mechanisms from various types of deposits, sediments, biological growths and other unwanted formations [1]. In medicine and bioengineering, ultrasonic cavitation is used to deliver drugs to the body, destroy kidney stones and treat some forms of cancer; studies are being conducted on the possibility of directing and focusing cavitation to remove affected tissue [2– 4]. Cavitation action intensifies the processes of dissolution and extraction, and is also used in homogenization, pasteurization, and

ISSN: 2835-3730 Website: econferenceseries.com

the production of emulsions and suspensions [5]. Cavitation also promotes the effective formation of dispersed fuel composites. Water-coal, water-fuel oil, and water-diesel emulsions have already proven their economic and environmental benefits [6– 8]. Cavitation treatment of mixture elements generates a local energy concentration, which is sufficient for diffusion of the substance components at the micro level, which allows obtaining a highly dispersed product resistant to destruction and rapid reverse aggregation [9]. The action of hydrodynamic cavitation leads to decomposition (mechanolysis) of water, which results in a change in its structure with the formation of free hydrogen bonds, which causes increased activity and reagent capacity. In addition to mechanolysis, cavitation activation of water contributes to a change in the degree of uniformity of impurity distribution throughout the volume of the system, their aggregation and disaggregation [10]. Similar cavitation processes are used for purification, disinfection, decontamination, removal of natural organic substances in drinking water [11]. The use of hydrodynamic cavitation in water purification began to be studied more intensively in the 90s of the twentieth century and continues to this day. It was noted that hydrodynamic cavitation is more effective compared to acoustic cavitation. The use of sonochemical reactors creates significant problems in design and operation in a large-scale mode due to significantly lower energy efficiency and higher operating costs [12]. Hydrodynamic cavitation action is usually formed during flow compression, constrictions in the form of nozzles, nozzles, etc. [12– 14]. However, projects are emerging where the cavitation effect on the liquid is realized under conditions of vortex centrifugal motion [15, 16]. This paper considers the possibility of using a centrifugal pump (CP) as a cavitation generator when pumping liquid. The cavitation region in the interblade channel, formed at constant characteristics inherent in this type of pump (flow rate, total pressure, rotation frequency), is analyzed due to a change in the linear dimensions of the impeller. The geometry construction and the analysis of the pump operation were performed using the capabilities of mathematical modeling of hydrodynamic processes by means of the ANSYS CFX finite element package. This tool is widely used for optimization and design of various parts of the pump [17], their multifunctional analysis, including taking into account cavitation [18– 21].

Water scarcity has become an increasingly pressing issue in Central Asian countries such as Kazakhstan, Uzbekistan, and Turkmenistan, especially during the years 2010-2020. The region's arid climate and the overuse of water resources for agricultural purposes have led to the depletion of vital water supplies. Aging

ISSN: 2835-3730 Website: econferenceseries.com

infrastructure and inefficient water pumps compound the challenge, resulting in significant water loss and reduced agricultural productivity. As water demand continues to exceed supply, the need for modernizing water pump systems and adopting sustainable irrigation practices has become critical to ensuring water security and supporting the livelihoods of millions in the region. Use the following sources if appropriate. Therefore, early-stage monitoring and prediction of off-design operation conditions for centrifugal pumps have become essential.

Regular monitoring is essential for the uninterrupted and efficient functioning of pump units in industrial settings. Vibrations in pump units can indicate various issues, ranging from misalignments to bearing failures. Therefore, it is crucial to recognize the patterns and behaviors in these vibrations to ensure operational integrity.

Advancements in vibrodiagnostic tools and techniques have enabled the development of sophisticated methods for condition monitoring. These methods leverage innovations in sensor technology and signal processing to foresee potential faults before they lead to failures. Despite these technological strides, accurately interpreting the data to distinguish between normal operational noise and signals of potential issues remains a challenge. Additionally, integrating these diagnostic systems into existing pump unit operations often requires overcoming logistical and technical obstacles.[22]

This study aims to contribute valuable insights and innovative solutions for industry professionals by exploring the applicability of cutting-edge vibrodiagnostic indicators. It focuses on enhancing the reliability and effectiveness of horizontal centrifugal pumps used in-house and bridges the gap between theoretical vibrodiagnostic principles and practical, on-the-ground applications.

Providing relevant background information is essential to show a solid understanding of the main issues and concepts that support the entire study. The background should clarify how the research question was developed and connect to the significance and importance of the topic.[23]

To sum up, monitoring the condition of pump units and identifying potential faults or failures is crucial to ensure their reliable and efficient operation. Vibrodiagnostic indicators provide valuable information about vibration patterns and behavior, and innovative methods for condition monitoring have been developed. However, accurately interpreting the data and integrating diagnostic systems into existing operations remain challenging. This study aims to provide valuable insights and solutions for industry professionals. This study focuses on the use of vibrodiagnostic

ISSN: 2835-3730 Website: econferenceseries.com

indicators to monitor and maintain the reliability of pump units in industrial settings.[24]

Aims and Objectives

The aim of this study is to investigate the use of state-of-the-art technology, such as vibration analysis and electrical motor current signals, for detection. and diagnosis of incipient faults in in-house horizontal centrifugal pumps. The objectives of this study are:

1. To assess the suitability of single-value indicators derived from vibration signals for monitoring the operation conditions of centrifugal pumps.
2. To evaluate the comparative advantages of wavelet transform analysis over traditional methods in analyzing vibrodiagnostic data.
3. To develop diagnostic algorithms that can accurately classify pumps as having above or below 10% flow loss and achieve a prediction accuracy as high as 97.9%.

By achieving these aims, this study hopes to enhance the reliability and effectiveness of pump units in industrial settings, thereby improving operational efficiency and reducing maintenance costs. The completion of the sentence would be: "This study aims to investigate the use of vibrodiagnostic indicators in monitoring and maintaining the reliability of pump units."[25] This study aims to investigate the use of vibrodiagnostic indicators in monitoring and maintaining the reliability of pump units, to enhance operational efficiency and reduce maintenance costs in industrial settings. "This study aims to investigate the use of vibrodiagnostic indicators in monitoring and maintaining the reliability of pump units, to enhance operational efficiency and reduce maintenance costs in industrial settings"[26]. This study aims to investigate the use of vibrodiagnostic indicators in monitoring and maintaining the reliability of pump units, with the ultimate goal of enhancing operational efficiency and reducing maintenance costs in industrial settings. This study aims to investigate the use of vibrodiagnostic indicators in monitoring and maintaining the reliability of pump units, with the ultimate goal of enhancing operational efficiency and reducing maintenance costs in industrial settings. This study aims to investigate the use of vibrodiagnostic indicators in monitoring and maintaining the reliability of pump units, with the ultimate goal of enhancing operations.

Methods

On the one hand, the study will utilize vibration analysis and electrical motor current signals to monitor the condition of the pump units. These diagnostic methods will involve the analysis of the vibration patterns and frequencies in different directions, as well as the examination of electrical motor current signals. Additionally, wavelet transform analysis will be used to analyze the vibrodiagnostic data and compare its advantages with traditional methods. The study will also incorporate fuzzy logic principles to enhance fault diagnosis and condition monitoring of the pumps.

On the other hand, experimental testing will be carried out to validate the effectiveness of the proposed vibrodiagnostic indicators in predicting pump unit reliability. Using controlled experiments, the researchers will subject pump units to various operating conditions and measure their vibration patterns and electrical motor current signals.

The Finite Element Analysis aspect of the study was conducted using the ANSYS software suite (version 5.3), which allowed for detailed modeling of stress distribution in pump unit components. Throughout the process, several user guides and resources proved indispensable, as detailed in the 'Additional Resources' section. The results of this study will provide valuable insights into the use of vibrodiagnostic indicators for monitoring and maintaining the reliability of pump units.

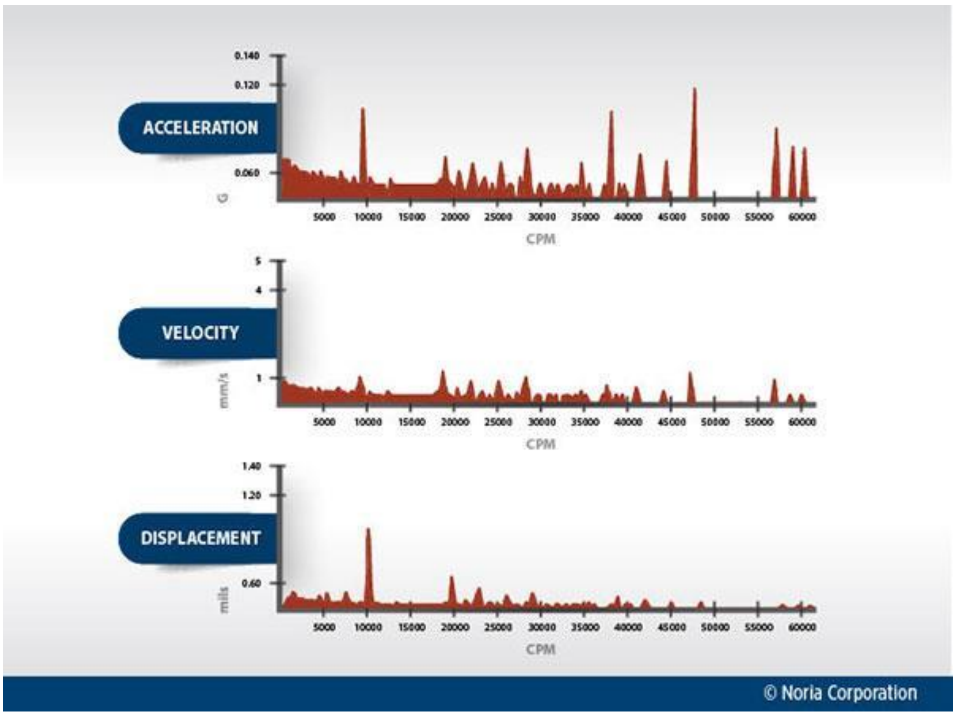

Figure 1: Vibration Analysis Graphs for Predictive Maintenance in Water Pump Systems by Noria Corporation.

The image of Figure 1 displays three separate line graphs, each depicting different types of measurements related to vibration analysis. These measurements are labeled as:

A. ACCELERATION: It has a y-axis that ranges from 0 to 0.140 with an unspecified unit (likely g's which stand for gravitational force) and an x-axis labeled as CPM (Cycles Per Minute), ranging approximately from 0 to 60000. This graph shows various spikes in acceleration throughout the range.

B. VELOCITY: This graph's y-axis spans from 0 to 5 with an undefined unit (possibly in inches per second or millimeters per second, common units for velocity in vibration analysis). The x-axis is the same as the ACCELERATION graph, suggesting these data sets are related to the same events or machinery. The pattern is somewhat similar to that of the acceleration graph but smoothed out.

C. DISPLACEMENT: The y-axis extends from 0 to 1.80, with no units specified (could be in mils which stands for thousandths of an inch or in micrometers). The x-axis matches the other two graphs. The displacement graph appears to have fewer and smaller spikes compared to the velocity and acceleration graphs.

These graphs are typically used in predictive maintenance to analyze the condition of machinery and to predict when maintenance should be performed based on vibration patterns. The presence of the "Noria Corporation" logo suggests that this is an image from a company that might specialize in machinery maintenance or optimization.

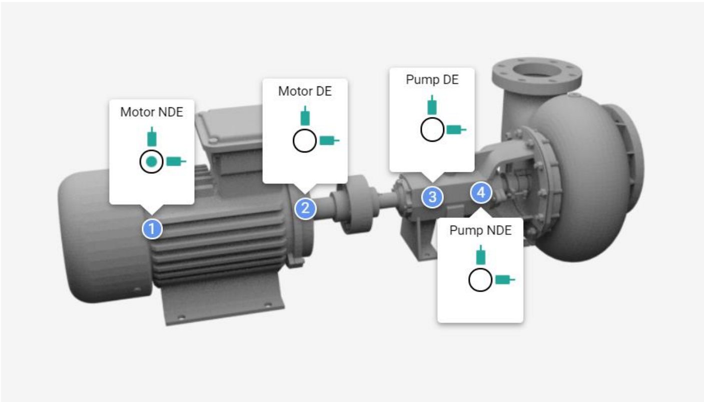

Figure 2: Motor-Pump Assembly Diagram with Motor and Pump Component Labels for Monitoring.

The image of Figure 2 shows a diagram of a motor pump assembly with labels indicating different components and their positions. There are two main parts: the motor and the pump, and each has two points identified for, I presume, monitoring or connection purposes. They are labeled as follows:

I. "Motor NDE" – This is likely referring to the Non-Drive End of the motor, which is the end opposite where the power input occurs.
II. "Motor DE" – This indicates the Drive End of the motor, where the shaft transmits the mechanical power to the pump.
III. "Pump DE" – Similar to the motor, this is the Drive End of the pump where it is connected to the motor and receives mechanical energy.
IV. "Pump NDE" – This is the Non-Drive End of the pump, opposite to the drive end.

These labels are helpful for identifying the parts during installation, maintenance, or troubleshooting of the motor pump assembly.

The graphs feature complex wave patterns, indicating that the vibration signals are not simple but contain various frequencies and intensities. The spikes on the graphs might indicate points of interest that could correspond to mechanical issues or harmonic frequencies of the machine being analyzed.[27]

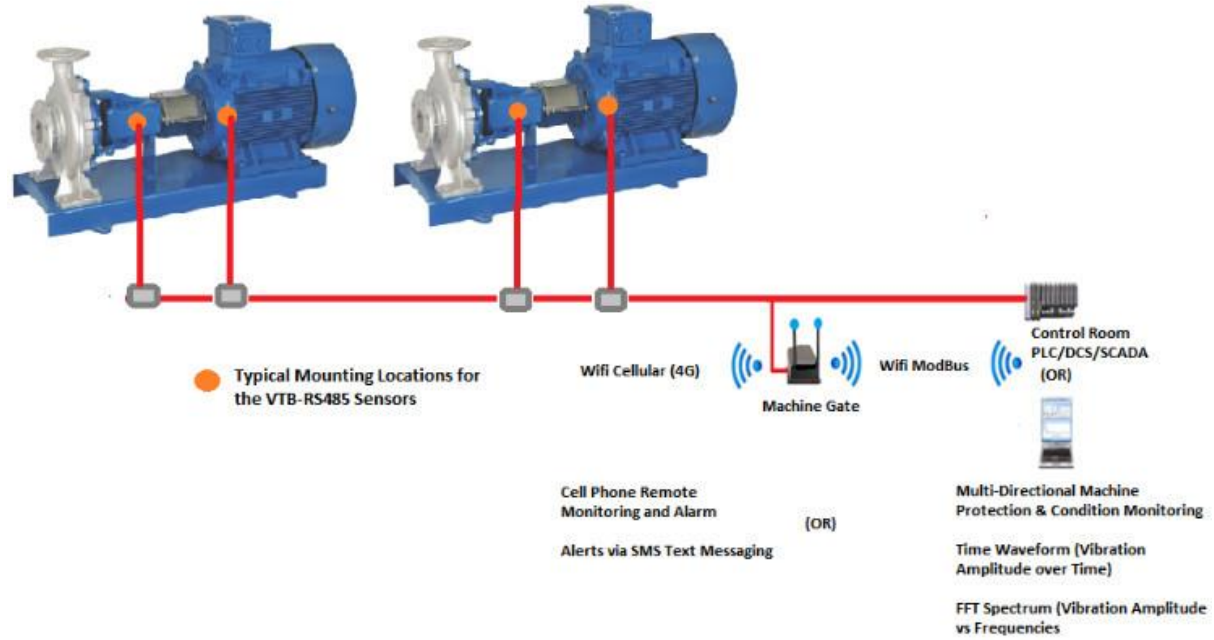

Figure 3: Industrial Machine Monitoring System with Wireless Sensors and Remote Alert

The image of Figure 3 based on the content you supplied, the revised headings for your abstract and keywords might look like this:

On the left side, there are three industrial pumps or motors, each equipped with a sensor labeled as "Typical Mounting Locations for the VTB-RS485 Sensors." These sensors are connected via a red line, representing data transmission, to a central hub or gateway labeled as "WiFi Cellular (4G)." This suggests that the sensors collect data and send it wirelessly over a cellular network.

Next to the central hub is a depiction of a "Machine Gate," which is likely the physical point where the machine's data is collected or monitored. The red data transmission line continues from the machine gate to the right, where there is a representation of a "Control Room." The control room is associated with icons indicating "PLC/DCS/SCADA (IOR)," which are common types of industrial automation and monitoring platforms.[28]

Alongside the main schematic, there are several textual elements describing the functionality of the system:

1. "Cell Phone Remote Monitoring and Alarm" - suggesting the system has the capability to remotely monitor the equipment and send alarms via cell phone communication.
2. "Alerts via SMS Text Messaging" - highlighting a feature where the system can send text message alerts, probably when certain thresholds are met or abnormalities are detected.
3. "Multi-Directional Machine Protection & Condition Monitoring" - indicates that the system provides comprehensive monitoring and protection against various types of faults or conditions of the machinery.
4. "Time Waveform (Time Amplitude over Time)" - a type of data analysis to show how a variable, such as vibration amplitude, changes over time.
5. "FFT Spectrum (Vibration Amplitude vs Frequencies)" - a reference to Fast Fourier Transform, a mathematical technique to analyze the frequencies within a signal, often used to diagnose equipment conditions based on vibration data.

Overall, this image is a visual presentation of an industrial monitoring setup that features vibration sensors, cellular data transmission, and advanced data analysis for preventative maintenance and condition monitoring of machinery. The system leverages modern communication technology to provide real-time updates and alerts regarding the equipment's operating conditions.[29]

Results and discussions

The examination and comparison of the vibration patterns and electric motor current signals offer valuable insights into the condition and dependability of the pump units. By utilizing these vibrodiagnostic markers, it becomes feasible to identify and pinpoint any potential malfunctions or irregularities in the pump units. Furthermore, the wavelet transform analysis proves to be a highly effective method in analyzing the vibrodiagnostic data, offering comparative advantages over traditional methods.

The application of fuzzy logic principles in fault diagnosis and condition monitoring further enhances the accuracy and reliability of the pump unit evaluations.

The experimental testing carried out to validate the proposed vibrodiagnostic indicators confirms their effectiveness in predicting pump unit reliability.

- The following resources were utilized extensively in our ANSYS-based analysis and can be highly beneficial for similar applications:

- ANSYS User's Manual, Version 5.3: Provided foundational guidance on the software's features and operation.

- ANSYS Learning Forum: Served as a platform to resolve specific technical challenges encountered during simulations.

Tutorials created internally and shared among the research team covered specialized methods for vibrodiagnostic analysis, enhancing the utilization of ANSYS software capabilities. In conclusion, the utilization of vibrodiagnostic indicators, including vibration patterns and electric motor current signals, along with the application of fuzzy logic principles and wavelet transform analysis, has proven to be an effective approach for monitoring and maintaining the reliability of pump units.

Literature Review

In the ever-evolving field of machine condition monitoring and fault diagnosis, recent research has made significant strides in enhancing the efficiency, accuracy, and practicality of these crucial processes. Building on the foundational work that emphasizes the role of vibrodiagnostic indicators in monitoring mechanical reliability[30], a collection of studies has presented innovative methods that promise to revolutionize preventative maintenance and fault detection across various applications.

A key development in this realm is the application of acoustics-based techniques for the condition monitoring of helical gearboxes. By leveraging modulation signal bispectrum analysis, researchers have successfully filtered out noise to isolate the characteristics indicative of gear deterioration. This approach not only allows for remote monitoring but also signals an order-of-magnitude improvement in diagnostic effectiveness.[31]

Furthermore, the use of on-device, intelligent sensors proves to be a highly effective strategy in agricultural settings, providing a decentralized and cost-effective solution for monitoring water pump equipment. Remarkably, this method achieved a 93% accuracy in malfunction detection through vibration data analysis, showcasing the potent combination of inexpensive microcontrollers, sensors, and neural network models.

Suggestions for industry adoption, future research directions, and potential economic impact analysis

After an extensive review of advancements in machine condition monitoring and fault diagnosis, the following suggestions are put forward to benefit from the research findings:

1. Invest in Advanced Diagnostic Tools

Industries should consider investing in the latest diagnostic technologies such as CWT-PARAFAC-IPSO-SVM algorithms and intelligent sensors. This could enhance their predictive maintenance strategies by allowing for early detection of potential issues, preventing machinery breakdown and costly disruptions.

2. Develop Decentralized Monitoring Systems

The benefits of cost-effective, on-device intelligent sensors should be harnessed to create decentralized monitoring systems, particularly in agricultural settings. Such tools can lead to significant improvements in operational efficiency.

3. Foster Cross-Disciplinary Collaboration

Experts in mechanical engineering, data science, and machine learning should collaborate to refine and develop multi-sensor fusion strategies for more sophisticated fault diagnosis and reliability assessment.

4. Utilize Big Data Analytics

Organizations should leverage big data analytics to process the vast amount of data collected from sensors for real-time decision-making and predictive insights.

5. Focus on Training and Development

To maximize the effectiveness of new diagnostic technology, industry professionals, including engineers, technicians, and operators, should receive training in the latest predictive maintenance techniques and data analysis skills.

6. Promote Research in Multi-Sensor Fusion

Future research should focus on improving multi-sensor fusion techniques and exploring the integration of different types of sensors to provide a comprehensive view of machine health.

7. Evaluate Economic Impact

Conduct studies to assess the economic benefits of adopting advanced diagnostic methods, including return on investment analysis and impact on overall productivity and profitability.

Conclusion

After analyzing recent advancements in machine condition monitoring and fault diagnosis, the literature strongly supports the integration of vibroacoustic and other advanced sensor-based diagnostic indicators. These methods show exceptional promise in various industries for enhancing the accuracy and efficiency of predictive maintenance techniques.

Studies reviewed demonstrate a growing trend toward adopting sophisticated signal processing and diagnostics, particularly with the development and application of algorithms like CWT-PARAFAC-IPSO-SVM, which optimize the capabilities of existing technologies and introduce new benefits. Coupled with intelligent sensors and multi-sensor fusion strategies, these algorithmic approaches represent a significant leap in the industrial and agricultural sectors' ability to proactively manage and maintain machinery.

Moreover, the push toward decentralized monitoring systems with smart sensors capable of accurate malfunction detection highlights an ongoing shift toward more affordable, scalable, and effective predictive maintenance solutions. These technological innovations not only increase machinery uptime and prevent unexpected failures but also reduce maintenance costs, thereby increasing overall profitability and productivity across a range of operational contexts.

The literature review's findings signify a broader movement in the maintenance industry towards data-driven, machine learning-enhanced strategies, which are essential for the next generation of industrial and agricultural operational excellence. The adaptability and advanced capabilities of these diagnostic tools portend a future where maintenance is not merely a reactive task, but an integral, intelligent, and anticipatory component of everyday operations.

In effect, the literature underscores the critical role of emerging technologies in the evolution of maintenance from a traditionally cost-centric concern to a strategic, value-adding element in the pursuit of operational resilience, sustainability, and competitiveness. As such, stakeholders and practitioners in the field of maintenance are encouraged to leverage these technological advances to stay ahead of the curve in an increasingly complex and demanding global business environment.

References

[1] R. Ergashev, F. Bekchanov, A. Atajanov, I. Khudaev and F. F. Yusupov. "Vibrodiagnostic method of water pump control". E3S web of conferences. vol. 264. pp. 04026-04026. Jan. 2021. 10.1051/e3sconf/202126404026.

[2] S. K. Ratan, T. Anand and J. Ratan, "Formulation of Research Question – Stepwise Approach".

[3] M. Agron, R. C. Silacci and P. Klein, "Challenges in designing and integrating a multi-operations systems solution".

[4] Р. И. Сулейманов, M. Khabibullin and Р. И. Сулейманов, "Monitoring the technical condition of the electric centrifugal pump during the repair process".

[5] Y. Luo, Y. Han, S. Yuan and J. Yuan, "Research on the Single-Value Indicators for Centrifugal Pump Based on Vibration Signals".

[6] Y. Luo, Y. Han, S. Yuan and J. Yuan, "Research on the Single-Value Indicators for Centrifugal Pump Based on Vibration Signals".

[7] Y. Lin, S. Wei and C. Huang, "Intelligent Manufacturing Control Systems: The Core of Smart Factory".

[8] W. Zhao, S. Wang and Q. Xue, "Design and Implementation of Portable Petrochemical Equipment Vibration Monitor Based on Multi-Layer Architecture".

[9] E. A. Burda, G. V. Zusman, I. S. Kudryavtseva and A. P. Naumenko. "An Overview of Vibration Analysis Techniques for the Fault Diagnostics of Rolling Bearings in Machinery". Shock and vibration. vol. 2022. pp. 1-14. Dec. 2022. 10.1155/2022/6136231.

[10] K. Lu, J. Gu, H. Fan, X. Sun, B. Li and F. Gu. "Acoustics Based Monitoring and Diagnostics for the Progressive Deterioration of Helical Gearboxes". Chinese journal of mechanical engineering/Chinese Journal of Mechanical Engineering. vol. 34. no. 1. Aug. 2021. 10.1186/s10033-021-00603-1.

[11] "Gear Signal Fault Diagnosis Based on Wavelet Transform Denoising".

[12] D. Loukatos, M. Kondoyanni, G. Alexopoulos, C. Maraveas and K. G. Arvanitis. "On-Device Intelligence for Malfunction Detection of Water Pump Equipment in Agricultural Premises: Feasibility and Experimentation". Sensors. vol. 23. no. 2. pp. 839-839. Jan. 2023. 10.3390/s23020839.

[13] Y. Zhu, G. Li, R. Wang, S. Tang, S. Hong and K. Cao. "Intelligent Fault Diagnosis of Hydraulic Piston Pump Based on Wavelet Analysis and Improved AlexNet". Sensors. vol. 21. no. 2. pp. 549-549. Jan. 2021. 10.3390/s21020549.

[14] M. Cecchini, F. Piccioni, S. Ferri, G. Coltrinari, L. Bianchini and A. Colantoni. "Preliminary Investigation on Systems for the Preventive Diagnosis of Faults on Agricultural Operating Machines". Sensors. vol. 21. no. 4. pp. 1547-1547. Feb. 2021. 10.3390/s21041547.

[15] Y. Sun and X. Han. "Research on Vibration Fault Diagnosis Technology of Steam Turbine Unit in Power Plant Based on Wavelet Theory". IOP conference

series. Earth and environmental science. vol. 631. no. 1. pp. 012096-012096. Jan. 2021. 10.1088/1755-1315/631/1/012096.

[16] D. Sarathkumar, M. Srinivasan, A. A. Stonier, R. Samikannu, D. N. Rao and R. A. Raj, "A Technical Review on Classification of Various Faults in Smart Grid Systems".

[17] S. Selcuk, "Predictive maintenance, its implementation and latest trends".

[18] R. N. Suleymanov and S. R. Suleymanov, "On the choice of a failure criterion for pumping units based on the results of vibration spectra measurement".

19. Овсянников Б.В., Боровский Б.И. Теория и расчет аг регатов питания жидкостных ракетных двигателей. М: Машиностроение. 1986. С. 185189

20. Исследование влияния подачи воздуха во всасыва ющую магистраль центробежного насоса на его виб роакустические характеристики / А.А. Иголкин, А.Н. Крючков, А.Б. Прокофьев, Е.В. Шахматов // Вестник СГАУ. 2002. №1. С. 7883.

21. Zarnitsyn V., Rostad C. A., Prausnitz M. R. Modeling transmembrane transport through cell membrane wounds created by acoustic cavitation. Biophysical Journal, 2008, vol. 95, no. 9, pp. 4124– 4138. doi: 10.1529/biophysj.108.131664

22. Sinden D. Modelling cavitation in liver tissue under highintensity focused ultrasound. British Applied Mathematics Colloquium. Birmingham, 2011.

23. Promtov M.A. Prospects of cavitation technologies application for intensification of chemical technological processes. Transactions of the TSTU, 2008, vol. 14, no. 4, pp. 861– 869. (In Russian)

24. Sheng H.-Z., Zhang Z.-P., Wu C.-K. Study of atomization and micro-explosion of water-in-diesel fuel emulsion droplets in spray within a high temperature, high pressure bomb. International Symposium COMODIA, 1990, pp. 275– 280.

25. Seifi M.R., Hassan-Beygi S.R., Ghobadian B., Desideri U., Antonelli M. Experimental investigation of a diesel engine power, torque and noise emission using water-diesel emulsions. Fuel, 2016, vol. 166, no 15. pp. 392– 399. doi: 10.1016/j.fuel.2015.10.122

26. Fahd M.E.A., Wenming Y., Lee P.S., Chou S.K., Yap C.R. Experimental investigation of the performance and emissioncharacteristics of direct injection diesel engine by water emulsion diesel under varying engine load condition. Applied Energy, 2013, vol. 102, pp. 1042– 1049. doi: 10.1016/j.apenergy.2012.06.041

27. Spiridonov E.K. Characteristics and Calculation of Cavitation Mixers. Procedia Engineering, 2015, vol. 129, pp. 446– 450. doi: 10.1016/j.proeng.2015.12.148.

28. Kulagin V.A. Grishchenko E.P. Hydro and Gas Dynamics: Textbook. Krasnoyarsk, IPK SFU Publ., 2009, 278 p. (In Russian)
29. Cehovin M., Medic A., Scheideler J. et al. Hydrodynamic cavitation in combination with the ozone, hydrogen peroxide and the UV-based advanced oxidation processes for the removal of natural organic matter from drinking water. Ultrasonics Sonochemistry, 2017, vol. 37, pp. 394– 404. doi: 10.1016/j.ultsonch.2017.01.036
30. Mishra K.P., Gogate P.R. Intensification of degradation of Rhodamine B using hydrodynamic cavitation in the presence of additives. Separation and Purification Technology, 2010, vol. 75, no. 3, pp. 385– 391. doi: 10.1016/j.seppur.2010.09.008
31. Sarc A., Stepisnik-Perdih T., Petkovsek M., Dular M. The issue of cavitation number value in studies of water treatment by hydrodynamic cavitation. Ultrasonics Sonochemistry, 2017, vol. 34, pp. 51– 59. doi: 10.1016/j.ultsonch.2016.05.020.