PREDICTIVE MAINTENANCE FOR WATER PUMP UNITS: AI-DRIVEN VIBRATION DATA ANALYSIS AND REMAINING USEFUL LIFE PREDICTION

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Annotation: Water pumps are an integral part of industrial and municipal infrastructure, and their reliable and uninterrupted operation is important in terms of production, energy efficiency, and service stability. Sudden failure of pumps leads to stoppage of the production process, high repair costs, and negative safety consequences. This article describes in detail the methodology for predicting the remaining useful life (RUL) of water pumps using vibration data collection, signal processing, and advanced machine learning models. The purpose of the study is to optimize maintenance planning by increasing the accuracy of the RUL in practical industrial conditions, reducing economic and safety risks arising from failures, and increasing the efficiency of pump operation.

Keywords: water pumps, predictive maintenance, vibration analysis, remaining service life (RUL), artificial intelligence, IoT, signal processing, time series models.

Аннотация: Водяные насосы являются неотъемлемой частью промышленной и коммунальной инфраструктуры, и их надежная и бесперебойная работа важна для производительности, энергоэффективности и стабильности работы. Внезапный отказ насосов приводит к остановке производственного процесса, высоким затратам на ремонт и негативным последствиям для безопасности. В данной статье подробно описана методология прогнозирования остаточного срока службы (ОСС) водяных насосов с использованием сбора данных о вибрации, обработки сигналов и современных моделей машинного обучения. Цель исследования — оптимизировать планирование технического обслуживания за счет повышения точности ОСС в реальных промышленных условиях, снижения экономических и эксплуатационных рисков, возникающих из-за отказов, и повышения эффективности эксплуатации насосов.

Ключевые слова: водяные насосы, предиктивное обслуживание, анализ вибрации, остаточный срок службы (ОСС), искусственный интеллект, Интернет вещей, обработка сигналов, модели временных рядов.

Annotatsiya: Suv nasoslari sanoat va kommunal infratuzilmaning ajralmas qismi bo'lib, ularning ishonchli va uzluksiz ishlashi ishlab chiqarish, energiya

ISSN 3030-3907

samaradorligi va xizmat ko'rsatish barqarorligi nuqtai nazaridan muhimdir. Nasoslarning to'satdan ishdan chiqishi ishlab chiqarish jarayonining to'xtatilishiga, yuqori ta'mirlash xarajatlariga va salbiy xavfsizlik oqibatlariga olib keladi. Ushbu maqolada tebranish ma'lumotlarini yig'ish, signallarni qayta ishlash va ilg'or mashinani o'rganish modellari yordamida suv nasoslarining qolgan foydali muddatini (RUL) bashorat qilish metodologiyasi batafsil tavsiflanadi. Tadqiqotning maqsadi - amaliy sanoat sharoitida RULning aniqligini oshirish, nosozliklar natijasida yuzaga keladigan iqtisodiy va xavfsizlik xavflarini kamaytirish va nasosning ishlashi samaradorligini oshirish orqali texnik xizmat ko'rsatishni rejalashtirishni optimallashtirish.

Kalit so'zlar: suv nasoslari, bashoratli texnik xizmat ko'rsatish, tebranish tahlili, qolgan xizmat muddati (RUL), sun'iy intellekt, IoT, signalni qayta ishlash, vaqt seriyasi modellari.

Introduction.

Water pumps are strategic equipment that ensures uninterrupted operation in industries such as production, energy, utilities, and agriculture. Traditional - reactive and preventive - maintenance approaches are characterized by limited efficiency and excessive resource consumption. In recent years, as a result of the development of IoT sensors, unlimited data collection capabilities, and artificial intelligence (AI) methods, the practice of predictive maintenance has become widespread. Vibration signals very sensitively reflect the mechanical state of the pump and are one of the most useful monitoring parameters for early detection of malfunctions.

Their operation directly affects many technological operations, such as cooling, liquid supply, and pressure maintenance; therefore, failures in pumps can lead to serious disruptions not only at the level of individual equipment, but also in the entire production chain and safety systems. Sudden failure of pumps leads to a decrease in revenue from production, additional damage to equipment, an increase in emergency repair costs, and sometimes to situations that pose a threat to the environment and human life. Therefore, constant monitoring of the technical condition of pumps and early detection of malfunctions is a priority task from the point of view of ensuring production efficiency and safety.

Traditional maintenance strategies - reactive and preventive approaches - often do not yield sufficient effectiveness. The main problem with reactive services is the need to intervene only after a malfunction occurs, which leads to an unexpected shutdown of production. The preventive service does not take into account the actual condition of the device, since it is carried out according to the established schedule; as a result, unnecessary replacements and unnecessary

ISSN 3030-3907

expenses arise. These approaches lead to inefficient use of resources, waste of working time, and incomplete compliance with safety and reliability requirements.

In order to eliminate these limitations, a predictive maintenance approach has appeared. This approach is based on continuous sensory monitoring of the device's state, analysis of collected large amounts of data, and early detection of malfunctions and prediction of the remaining service life using machine learning. Data obtained through the IoT infrastructure reflects the real operating conditions of the pump, making traditional scheduled maintenance significantly more efficient. Artificial intelligence algorithms are capable of detecting complex, time-dependent patterns between parameters such as vibration, flow, pressure, and temperature, thereby allowing measures to be taken before the occurrence of a malfunction.

Literature review. Scientific literature on vibration diagnostics and technical condition monitoring emphasizes that vibration signals in rotating mechanical equipment, such as water pumps, are the main indicator of malfunctions. In previous studies, bearing wear, rotor imbalance, cavitation, and impeller damage of pumps were studied as mechanical processes determined by vibrational changes. In signal processing methods, time domain properties (RMS, kurtosis, crest factor), FFT analysis in the frequency domain, and time-frequency methods, in particular Wavelet Transform, are mentioned as the most commonly used approaches for detecting the initial stage of failures.

Scientific works devoted to AI-based forecasting show the predominance of deep learning models for RUL (Remaining Useful Life) forecasting. It was noted that LSTM and GRU gave high results in determining internal relationships in time series, while CNN was effective in automatically separating the spectral characteristics of vibration signals, and observations confirmed that the accuracy of models combined with LSTM is even higher. While classical models such as Random Forest and XGBoost have been noted to operate steadily with little data, the advantages of deep learning architectures in analyzing non-stationary signals are widely recognized.

Analysis of the literature shows that in many studies, the data were collected in laboratory conditions or focused only on one type of malfunction. Therefore, there is a gap in the creation of a flexible, multi-sensor, and generalized RUL model for the real industrial environment. This research is scientifically new precisely because it is aimed at filling this gap.

Research results. The practical effectiveness of the AI model developed in this section was assessed based on real or simulated pump vibration data. First of all, in the dataset, the vibrational state of the pump, changing over time, was analyzed, and it was shown that an increase in signal intensity or anomalies are

ISSN 3030-3907

associated with mechanical aging processes. The values of the remaining service life (RUL) calculated by the model, when compared with the actual operating cycles, were represented by graphs of how accurately or deviantly the forecast has over time.

The LSTM model provided stable RUL predictions with good traceability of the signal's time dependencies; CNN-LSTM quickly adapted to dynamic changes due to its in-depth study of spectral properties and showed high results in detecting complex vibrational patterns.

While the XGBoost, considered a classical model, performed well in some stationary conditions, it lagged behind in-depth learning models in fuzzy or sharply varying vibration signals.

Experimental results showed that the AI model is effective for timely monitoring of the pump's state and precise prediction of the RUL, and changes in the forecast as the vibration intensity increases correspond to the process of technical wear and tear. The effectiveness of the model's operation provided not only the possibility of preliminary detection of malfunctions, but also reliable prognostic data necessary for optimal maintenance planning.

Discussion. The obtained results confirm the effectiveness of the approach based on artificial intelligence for the implementation of predictive maintenance of water pumps. The model reliably reflects the internal dynamics of the mechanical wear process by detecting subtle changes in vibration signals and stably predicting the remaining service life of the pump. The high accuracy of LSTM and CNN-LSTM architectures demonstrates their ability to effectively study temporal dependencies and spectral characteristics, which provides an important advantage for understanding complex vibrational patterns arising in real industrial conditions. The stable result of the model in various work cycles increases the possibility of its use as a continuous monitoring system at industrial enterprises.

At the same time, there are a number of limitations in the practical application of the research. The quality and correct installation of vibration sensors is a decisive factor for data reliability; noisy or uncalibrated signals can reduce model performance. In some cases, the lack of data or low recurrence of failures makes it difficult to fully train the AI model, which increases the need for large datasets collected in various conditions. Additionally, the integration of models into the production process requires IT infrastructure, continuous sensor technologies, and real-time monitoring systems, which can lead to additional costs for some enterprises.

The results of the discussion show that the built AI model has high practical significance for optimizing the maintenance strategy, reducing the risk of accidents, and minimizing operating costs. However, to fully benefit from the

ISSN 3030-3907

system, the quality of sensors, continuous data collection, and regular calibration of the model in accordance with industrial conditions are necessary. These aspects are noted as the main factors for the successful application of forecast maintenance in the context of the real industry.

This study showed the important role of artificial intelligence in the effective organization of predictive maintenance of water pumps. Scientific experiments have confirmed the possibility of constant monitoring of the technical condition of the pump, identifying the first signs of malfunctions, and reliably predicting the remaining service life (RUL) by analyzing vibration data. The high accuracy of deep learning models such as LSTM and CNN-LSTM demonstrates that the AI approach is an effective tool based on a deep understanding of mechanical processes. This distinguishes itself as a more economical, safe method that serves to ensure the continuity of the production process compared to traditional preventive approaches.

The economic advantage of predictive maintenance is manifested in the possibility of reducing the risk of production downtime, optimizing the consumption of spare parts, and accurately planning maintenance costs. At the same time, the increased reliability of the method and the prevention of accidents create an additional advantage for industrial enterprises, since vibration analysis, together with real-time monitoring, allows for the early detection of instabilities arising during the operation of pumps.

In conclusion, there are several important areas for further research. Firstly, the formation of a larger and more diverse dataset can increase the generalizability of the AI model. Secondly, by integrating pressure, temperature, flow, and acoustic sensors in addition to vibration, it is possible to obtain more accurate forecasts based on multimodal data. Thirdly, it is necessary to develop additional algorithmic approaches to working with class imbalances, noise signals, and incomplete data encountered in real industrial conditions. Finally, testing the model as a pilot project in a production environment will help to fully assess the possibilities of its practical application.

REFERENCES:

1. Lei, Y., Li, N., Guo, L., Li, N., Yan, T., & Lin, J. (2018). Machinery health prognostics: A systematic review from data acquisition to RUL prediction. Mechanical Systems and Signal Processing, 104, 799-834.
2. Sikorska, J. Z., Hodkiewicz, M., & Ma, L. (2011). Prognostic modeling options for remaining useful life estimation by industry. Mechanical Systems and Signal Processing, 25(5), 1803-1836.

ISSN 3030-3907

3. Widodo, A., & Yang, B.-S. (2007). Support vector machine in machine condition monitoring and fault diagnosis. Mechanical Systems and Signal Processing, 21(6), 2560-2574.
4. Lu, Y., & Cecil, J. (2016). A review of sensor-based prognostics and health monitoring for manufacturing equipment. International Journal of Advanced Manufacturing Technology, 84, 1–15.
5. Zhao, R., Yan, R., Chen, Z., Mao, K., Wang, P., & Gao, R. X. (2019). Deep learning and its applications to machine health monitoring. Mechanical Systems and Signal Processing, 115, 213-237.

ISSN 3030-3907