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ACCELEROMETER CALIBRATION METHOD FOR INDUSTRIAL EQUIPMENT VIBRATION DIAGNOSTICS

The subject of study in the article is the method of calibrating accelerometers as part of a digital platform for vibration diagnostics of industrial equipment. The goal is to increase the informativeness of the processes of vibration diagnostics of industrial equipment by developing and implementing IoT-oriented solutions based on smart sensors and actuators per the IEEE 1451.0-2007 standard. Tasks: justify the feasibility of using platform-oriented technologies for vibration diagnostics of industrial equipment and choose a cloud service for the implementation of the platform; develop software and hardware solutions of the IoT platform for vibration diagnostics of industrial equipment; calibrate the vibration diagnostics system and check the measurement accuracy. The methods used are the microservice approach, multilevel architecture, and assessing equipment state based on vibration data. We obtained the following results. The architecture of the IoT system for vibration diagnostics of industrial equipment developed and presented in the article is three-level. The level of autonomous sensors provides readings of vibration acceleration indicators and transmits data to the Hub level, which is implemented based on a BeagleBone single-board microcomputer through the BLE digital wireless data transmission channel. BeagleBone computing power provides work with artificial intelligence algorithms. At the third level of the server platform, the tasks of diagnosing and predicting the condition of the equipment are solved, for which the Dictionary Learning algorithm implemented in the Python programming language is applied. Verifying the accelerometer calibration method for vibration diagnostics of industrial equipment was performed using a unique stand. Conclusions. Correct operation of the entire system is confirmed by the coincidence of expected and measured results. In the next step, we plan the development of additional microservices that will provide the possibility of using time series analysis methods and modern artificial intelligence technologies for complex diagnostics and forecasting of the equipment state.

Key words: *Internet of things; digital platform; vibration diagnostics; calibration; accelerometer; industrial equipment.*

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МЕТОД КАЛІБРУВАННЯ АКСЕЛЕРОМЕТРІВ ДЛЯ ВІБРОДІАГНОСТИКИ ПРОМИСЛОВОГО ОБЛАДНАННЯ

Предметом дослідження в статті є методика калібрування акселерометрів у складі цифрової платформи вібраційної діагностики промислового обладнання. Мета – підвищити інформативність процесів вібродіагностики промислового обладнання шляхом розробки та впровадження IoT-орієнтованих рішень на основі інтелектуальних датчиків та актуаторів за стандартом IEEE 1451.0-2007. Завдання: обґрунтувати доцільність використання платформено-орієнтованих технологій для вібраційної діагностики промислового обладнання та вибрати хмарний сервіс для реалізації платформи; розробити програмно-технічні рішення платформи IoT для вібраційної діагностики промислового обладнання; відкалібрувати систему вібродіагностики та перевірити точність вимірювань. Використані методи - мікросервісний підхід, багаторівнева архітектура та оцінка стану обладнання на основі даних про вібрацію. Ми отримали наступні результати. Розроблена та представлена в статті архітектура системи IoT для вібродіагностики промислового обладнання є трирівневою. Рівень автономних датчиків забезпечує зчитування індикаторів віброприскорення та передає дані на рівень Hub, який реалізований на базі одноплатного мікрокомп’ютера BeagleBone через цифровий бездротовий канал передачі даних BLE. Обчислювальна потужність BeagleBone забезпечує роботу з алгоритмами штучного інтелекту. На третьому рівні серверної платформи вирішуються задачі діагностики та прогнозування стану обладнання, для чого застосований алгоритм Dictionary Learning, реалізований мовою програмування Python. Перевірку методики калібрування акселерометра для вібраційної діагностики промислового обладнання проведено на унікальному стенді. Висновки. Коректна робота всієї системи підтверджується збігом очікуваних і виміряних результатів. На наступному етапі ми плануємо розробку додаткових мікросервісів, які забезпечать можливість використання методів аналізу часових рядів і сучасних технологій штучного інтелекту для комплексної діагностики та прогнозування стану обладнання.

Ключові слова: *Інтернет речей; цифрова платформа; вібраційна діагностика; калібрування; акселерометр; промислове обладнання.*

Introduction. Today, the speed of implementation of technological innovations against the background of the development of new technologies (big data, cloud technologies, artificial intelligence, distributed ledger, the Internet of Things, and others) allows us to rebuild business and management models, remove intermediaries between producers of goods/services and their consumers, and implement direct transactions between them. Changes in technologies and business models in traditional industries within the framework of the fourth industrial revolution are carried out annually, which requires an increase in the speed of management decision-making (Evans, 2011). Today, to produce an innovative product or provide a service that meets users' requirements, it is necessary to combine the resources and competencies of several companies. The most significant conclusion of the article (Umair, 2021) is that to ensure the preparedness of industries for future pandemics, research and development are needed in various important directions, primarily digital equipment maintenance, end-to-end automation, etc.

Digital technologies provide homogeneity of data, their distribution, editability, and the ability to self-referencing and reprogram them. Such characteristics of digitization allow multiple inheritances to be implemented in distributed software applications when no single owner owns the platform's core and dictates the entire design hierarchy. By combining the modularity of physical goods with a layered software architecture, the resulting solutions can be arbitrarily combined through standardized interfaces, making products open to new uses after they are manufactured. In the concept of Industry 4.0, digitization replaces informatization (at the same time, informatization is a component of digitalization). A digital system must be created that can act independently, has analytical and prognostic functions, and solves tasks by itself.

Vibration diagnostic in the condition-based maintenance

For various mechanical systems, the quantitative measurement and subsequent analysis of motion characteristics occurring at different trajectories, amplitudes, and frequencies are critical to understanding the interaction of component systems and improving their performance and reliability. These tasks are central in many fields of application, such as production, transport, and energy generation, so vibration diagnostics is a fundamentally important method of assessing the condition of mechanical systems.

Implementing the concept of condition-based maintenance (CBM) (Sánchez, 2022), which monitors the equipment's actual condition to decide on the need for maintenance, has many advantages. CBM provides an opportunity to improve equipment reliability and reduce maintenance resource costs compared to a late-scheduled maintenance strategy. According to CBM, maintenance should only be performed when specific metrics show declining performance or future failures.

Ritter (Rytter, 1993) classified methods of the equipment state analyzing and detecting damage using vibration diagnostics on the following levels:

− determining the presence of damage in the structure;

− determination of the geometric location of the damage;

− quantitative assessment of damage severity;

− remaining service life prediction.

The primary attention is paid to the first three levels in the known publications. Papers (Koene, 2020, Villarroel, 2019)] provided constructive solutions and considered practical issues of confirming the accuracy of measurements but do not contain a description of methods for predicting the service life of the diagnosed equipment, which is undoubtedly the ultimate goal for the CBM concept (Park, 2001).

Smart sensors are a necessary component of a vibration diagnostics system. According to the IEEE 1451.0-2007 standard ([IEEE 1451.0-2007), sensors that provide functions that exceed the minimum sufficient to perform measurements should be considered intelligent. In addition to the digital interface and self-testing, this redundant sensor functionality simplifies its integration into applications in a networked environment and typically includes the following capabilities:

− self-identification and self-writing;

− presentation of not only the quantitative result of the measurement but also metrics, units of measurement, background history, notifications about activation, etc.;

− network access and ease of use (plug-and-play).

Overcoming the significant resource consumption of the CBM concept is possible by applying digital maintenance of industrial equipment and end-to-end automation based on IoT technologies. The well-known publication (Villarroel, 2019, Villacorta, 2021) considers in sufficient detail the construction of low-cost hardware and software solutions for vibration diagnostics, which is achieved by using modern microelectromechanical system (MEMS), while the authors ignore the issue of using IoT solutions for vertical integration of measuring devices with digital platforms. It is a platform-oriented solution using

BigData technologies, complex event processing (Complex Event Processing), and online analytics that provides new opportunities for fault diagnosis, state forecasting, and implementation of the CBM concept.

This paper proposes a method for calibrating microelectromechanical systems (MEMS) of accelerometers, which implement the contact method of vibration measurement, for IoT-oriented technology of industrial equipment vibration diagnostics.

MEMS accelerometers and their calibration

MEMS accelerometers are mechanical structures with freely moving elements. These moving elements can be susceptible to mechanical influences (shocks, shakes), usually much more sensitive than the electronic parts.

The accelerometer manufacturer, after a wide variety of tests, determines the output characteristics, which include sensitivity, frequency and phase response, resonant frequency, amplitude linearity, transverse sensitivity, temperature response, time constant, capacitance, and dependence on operating conditions, such as sensitivity to changes in temperature, magnetic fields, etc. Usually, the accelerometer requires additional calibration after installation at a specific location. During this calibration, we compare the measurement results with a reference accelerometer that has a guaranteed low sensitivity to noise under the calibration conditions. Both sensors are subject to general mechanical excitation, so their output signals can be directly compared (Larsonnier, 2019, Bilgic, 2017).

Modern standards of the ISO 16063 series (ISO 16063-11:1999) in four sections determine the requirements for vibration sensors and their calibration methods, including primary and secondary calibration, calibration in difficult conditions etc. The simplest way to calibrate a MEMS-accelerometer is to average the measurements (samples) values using the so-called scheme with a single calibration point. In a single-point calibration scheme, the accelerometer system is oriented so that one axis, usually the Z axis, is in a 1 g gravitational field, and the other X and Y axes are in a 0 g field. Standards recommend conducting at least ten samples with an interval of 0.1 s at a measurement frequency of 100 Hz.

Software and hardware solutions IoT platform for vibration diagnostics of industrial equipment.

Microsoft Azure IoT is Microsoft's cloud computing platform that provides infrastructure for creating and managing applications in the cloud (Tragos, 2015). The Azure Internet of Things Suite is an integrated service that uses all the relevant capabilities of Azure to connect devices. The Azure Internet of Things Suite captures a variety of data, integrates and organizes the flow of this data, manages it, analyzes it, and presents it in a format that helps people make relevant decisions. This highly analyzed and managed data also helps automate various processes and operations.

Thus, we choose Microsoft Azure IoT for further implementation, as this platform offers established solutions and its budget requirements are acceptable for startups at the initial stage.

Fig. 1 presents the architecture of the IoT platform of vibration diagnostics. The system's hardware is built on an STM32L476 microcontroller and a three-axis digital accelerometer IIS3DWB. The IIS3DWB accelerometer is installed on the monitoring object and is connected via the SPI bus to the microcontroller.

The IIS3DWB is a miniature three-axis digital capacitive accelerometer from STMicroelectronics with low power consumption, high resolution (16 bits), and a measurement range that can be programmed from ±2g, ±4g, ±8g, ±16g. The measurement result can be read through the digital interfaces SPI or I2C in 16-bit data. IIS3DWB has a bandwidth from 0.05 to 6000 Hz, which allows recording vibration with a frequency of 1000 Hz.

Digital platform database. A digital platform for vibration diagnostics of industrial equipment must store data for a long time. To achieve this goal, we choose the PostgreSQL DBMS. PostgreSQL has advanced features such as Multi-Version Concurrency Control (MVCC), asynchronous replication, and nested transactions (savepoints). The NoSQL database MongoDB was chosen for caching indicators on the BeagleBone AI Mini PC.

Peculiarities of the organization of customer interaction and the digital platform. The main feature of customer interaction and the digital platform organization is multilevel data transmission and processing because effective real-time vibration monitoring requires an autonomous network of sensors. It imposes certain limitations on data collection, analysis, and wireless transmission methods to reduce installation and operation costs and ensure high energy efficiency for extended autonomous operations.

Based on the above limitations, we choose an architecture with three levels.

1. The level of autonomous sensors that read indicators of vibration acceleration. These sensors are designed for autonomous operation for 6-12 months, depending on the survey frequency. To transfer indicators to the Hub level, digital wireless data transmission technology BLE (Bluetooth low energy) is used;

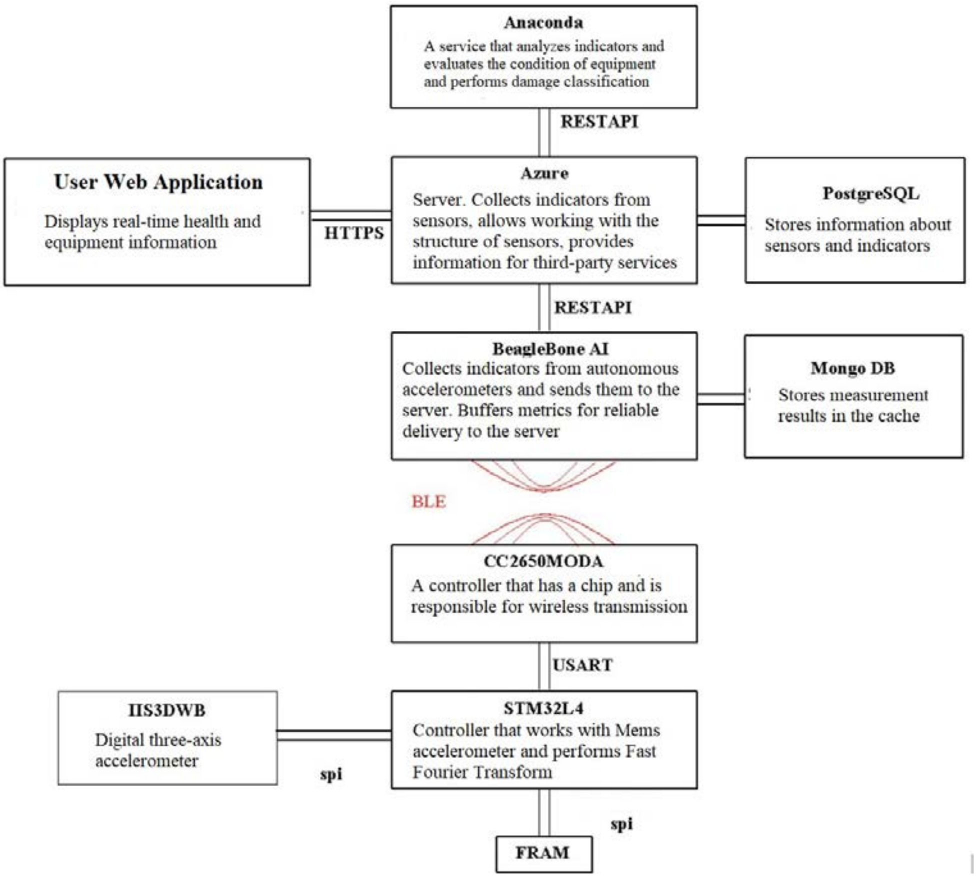

Fig. 1. Architecture of the IoT system of vibration diagnostics

2. The Hub level is implemented on a device based on a single-board microcomputer BeagleBone® AI (BeagleBone® AI,2021), which is designed to work with artificial intelligence algorithms. It has access to the Internet and a BLE module. Receives data from the level of autonomous sensors and transmits them to the server level. Depending on the selected analysis algorithm, it can pre-process the data before sending, significantly reducing the server's load.
3. The server-level provides an API for work with the structure of sensors and data to the client and third-party services.

Key algorithms of interaction between clients and the digital platform. We use the Discrete Fourier Transform (DFT) algorithm, which determines the frequency composition of discrete signals. The created software for calculating the DFT uses software from the FFTW library. Spectral data obtained from the DFT of vibration acceleration signals for each axis are recorded.

The digital platform provides customers with an assessment of the condition of the equipment in the form of classification: «normal operation» or «there is a problem.» When developing an evaluation algorithm, first of all, it is necessary to achieve the minimum requirement of the algorithm training when evaluating the equipment condition requires the smallest amount of labeled data. The algorithm needs to identify patterns and learn from unlabeled input data. Such techniques are called System Identification. The above requirements are satisfied by the algorithm based on Dictionary Learning, which was adopted as a basis.

The Python programming language was used to implement the algorithm because it has a significant library of tools for signal analysis, working with neural networks, and rich functionality. Since a microservice architecture was chosen during the construction of the system, the algorithm for evaluating the condition of the equipment is also presented as a separate service. It allows for easy and convenient scaling by adding new service instances.

Calibration of the IoT system for vibration diagnostics of industrial equipment

Implementation of the hardware part of the vibration diagnostics system. For the system suitability evaluation, we developed a stand with an electric motor and generator connected by a coupling, for which we use the Anycubic Mega S 3D printer. The stand simulates the working conditions of the pumping unit at the enterprise. One of the advantages of this stand decision is the ability to adjust and obtain the speed indicators not only on the built-in controller but also in the system, which allows the comparison of the speed of rotation and the obtained results of measurement by the vibration sensor.

The body of the stand houses a power supply unit and electronic-boards that control the motors on top: one of the motors simulates an electric motor, and the second - is a generator. A vibration sensor is attached to the body of the second engine. The control panel with a graphic interface allows for controlling the engine speed. The stand includes two stepper motors (one of them is a load), a stepper motor controller, an AC adapter, an STM32F4 Discovery test board, and a DC-DC converter. The control panel, built based on the STM32F437 controller, has a graphic touch screen for displaying information and accepting commands. Vibration control in such units is carried out at the load and engine nodes. Fig. 2 presents a scheme of the sensor mounting locations.

The measurement algorithm includes the following steps.

1. Initialization of the IIS3DWB accelerometer on the SPI bus.
2. Reading the value from the WHO_AM_I register and checking the accelerometer number.
3. Reading the IIS3DWB accelerometer settings.
4. Setting sampling values and interrupt mode.
5. Setting the measurement range and distributed capacity.
6. Start measurement.
7. Writing values to the buffer after an interrupt and waiting for the buffer to fill up.
8. After the buffer is filled, use the DFT to convert the series into a frequency representation.

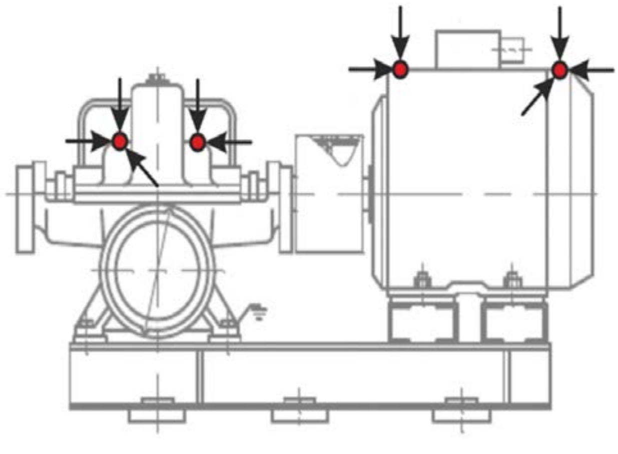

Fig. 2. Placement points of sensors for vibration control

9. Transmission via BLE.
10. After the transmission, repeat the steps starting with point 6.

Steps 6 and 9 of the measurement algorithm are the most energy-consuming. We check energy consumption in two stages: in all possible modes using measuring equipment and in long-term field testing.

Sensor calibration. Before starting the test, it is necessary to check the accuracy of the sensor calibration. For this, it is possible to use debugging with the JTAG interface - an industry standard for verifying designs and testing printed circuit boards.

Zero offsets are a vital accelerometer metric because they define the real acceleration threshold. Additional measurement errors occur when mounting a system with an accelerometer. Stresses can cause these errors in the printed circuit board during mounting or by applying different compounds to the component. We measure zero offsets according to ISO 16063-11:1999. These values are further stored in the OFFSET registers of the IIS3DWB accelerometer and are used for automatic error compensation. The content of each register is added to the measured acceleration value along the corresponding axis, and the results are placed in the data registers.

Calibration of sensors is carried out to evaluate the possible use of the hardware part, while the results obtained with the help of the debugger and visualization tools of the development environment are compared with the data visualized by the digital platform.

1. The arithmetic means of the measurements $\bar{x}$ for all measurements in each position (average at the start) and the standard deviation (SD) of the spread of measurements at points relative to the average - instability at the start we calculate as:

$$\bar{x} = \frac{1}{n}\sum_{j=1}^{n} x_j, \; SD = \sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(x_j - \bar{x}\right)^2} \quad (1)$$

For groups of positions in the runs, we calculate the average overall runs and the instability of the average from run to run, considering the rejection of anomalous measurements.

2. Compliance with the normal distribution law we check using the Shapiro–Wilk test (Wilk, 2015). It uses the sum of squared modules of the difference between the characteristic functions based on sample data and a normal distribution with weighting coefficients.

3. For noise spectral density analysis:

$$f(x) = a_0 + \sum_{n=1}^{\infty}\left(a_n \cos\frac{n\pi x}{L} + b_n \sin\frac{n\pi x}{L}\right) \quad (2)$$

we use discrete Fourier transform (DFT), which realizes transformation:

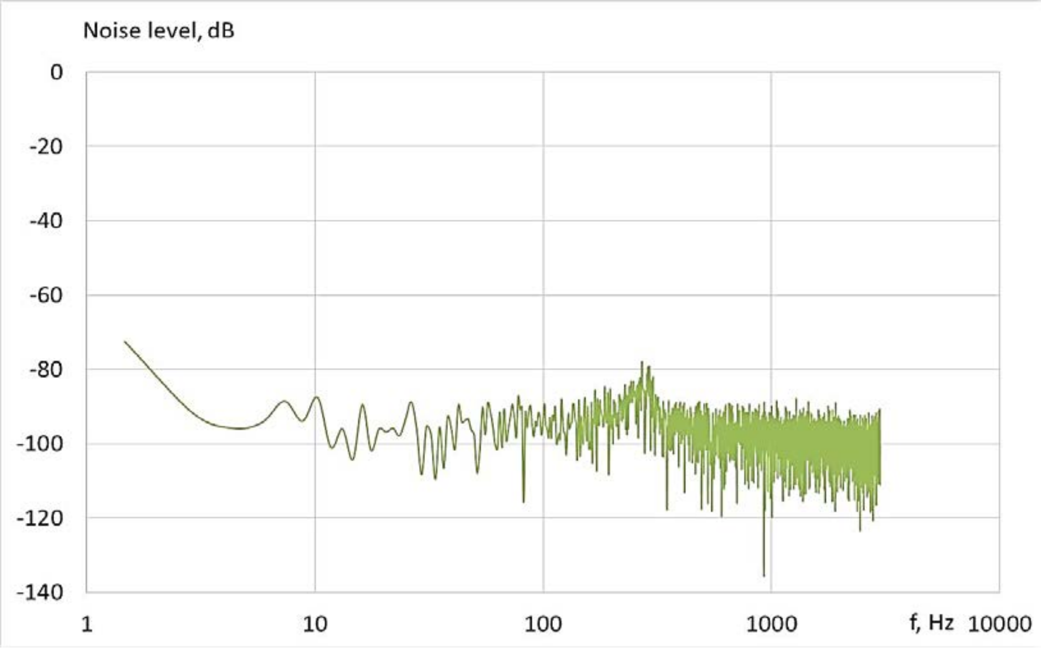

Fig. 3. The noise power spectral density of the IIS3DWB

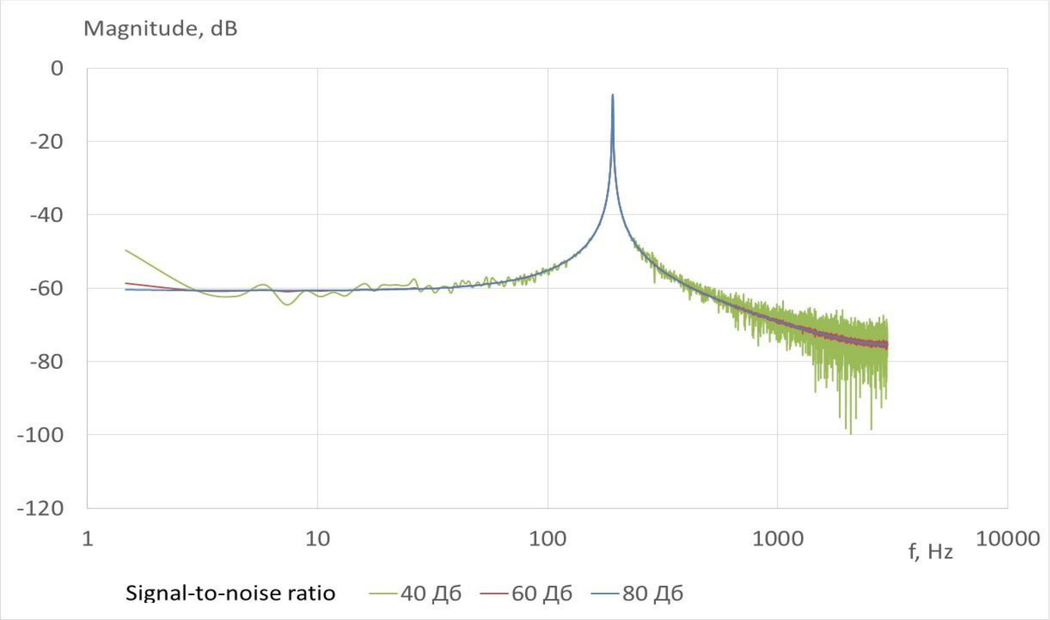

Fig. 4. Frequency response of vertical acceleration with the different signal-to-noise ratio

$$X_k = \sum_{j=0}^{n-1} x_j \cdot \left(\cos\left(\frac{2\pi}{n} kj \right) - i \cdot \sin\left(\frac{2\pi}{n} kj \right) \right). \quad (3)$$

Fig. 3 presents typical DFT results for IIS3DWB – 3D accelerometer; it is white noise in the target frequency range, which has equal intensity at different frequencies, giving it a constant power spectral density.

4. For the frequency response of the acceleration with different signal-to-noise ratios, we use imitation modeling (Fig. 4).

Comparison with analogs

We compare our system with three similar systems, each of which allows the connection of several accelerometers.

1. A system of IoT-connected devices for measuring and analyzing vibration (Koene, 2020).

2. A low-cost vibration measurement system for industrial applications, which, unlike all others, is the only one that uses wired data transmission and mains power (Villarroel, 2019).

3. A low-cost vibration measurement system for determining the condition of construction structures (Villacorta, 2021).

The developed system's technical and economic indicators, compared with analogs, have the following advantages.

The use of the specialized IIS3DWB accelerometer of the STM company, explicitly intended for vibration diagnostics, allowed it to increase the frequency range of measurements from 1000 Hz to 6000 Hz. Using the energy-efficient BLE 5.1 communication protocol and the STM32L476 microcontroller with the corresponding energy-saving algorithms allowed the operating time without the battery replacement to 1 year, while the analog system (Koene, 2020) requires replacement after only 8 hours. While maintaining approximately the same equipment cost and installation as in wireless analogs, a significant reduction in the cost of operation is ensured.

Conclusions. The article proposes an IoT-oriented technology for vibration diagnostics of industrial equipment. The architecture of the platform-oriented IoT system of vibration diagnostics of industrial equipment is three-level. Data from the level of autonomous sensors that read indicators of vibration acceleration are sent to the Hub level, which is implemented on the basis of a BeagleBone single-board microcomputer. At the level of the server platform, the tasks of diagnosing and predicting the condition of the equipment are solved, for which the Dictionary Learning algorithm, implemented in the Python programming language, is applied. The Microsoft Azure IoT platform (Azure Internet of Things Suite) provides the infrastructure for creating and managing applications in the cloud, integrates and organizes the flow of data, manages it, analyzes it, and presents it in a format that helps people make relevant decisions.

Calibration of the IoT system for vibration diagnostics of industrial equipment was performed using a unique stand, which provides the ability to calibrate sensors and check the accuracy of the measuring system. Correct operation of the entire system is confirmed by the coincidence of expected and measured results.

In the next step, we plan the development of additional microservices that will provide the possibility of using time series analysis methods and modern artificial intelligence technologies for complex diagnostics and forecasting of the equipment state.

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