Mechanical Vibration Monitoring System Based on Wireless Sensor Network

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Abstract—In order to solve the problem of mechanical vibration monitoring, a mechanical vibration monitoring system based on wireless sensor network was designed. First, the requirements of the hardware of the wireless rotating mechanical vibration monitoring system were analyzed. The monitoring node and base station node were designed. Then, based on the VisualBasic6.0 development tool, a software for monitoring the vibration of rotating machinery was designed. It had the functions of command control, data waveform display, and network topology display. In the mode of wireless mechanical vibration monitoring, the organization mode of the network, the transmission mode of data and the corresponding packet transmission format were improved. Finally, the reliable transmission of the data was verified. Compared with the traditional cable vibration sensor, the performance of the monitoring system was verified. The results showed that the wireless vibration monitoring system designed in this paper met the requirements for the monitoring of the vibration state of the rotating machinery.

Keywords—wireless sensor networks, mechanical vibration monitoring, rotating machinery vibration

1 Introduction

With the development of science and technology, modern industrial equipment has been upgraded, serialized, refined and automated. This has made outstanding contributions to reducing product cost, protecting environmental energy and improving economic efficiency. At the same time, it puts forward higher requirements for the maintainability of rotating machinery. If a large equipment fails, it will have an impact on the whole production line or even the whole factory, and the economic loss is immeasurable. In order to reduce the impact caused by mechanical faults, more and more members of staff began to study the wired monitoring technology for the vibration of rotating machinery. At present, many wire monitoring equipment for rotating machinery vibration has been successfully developed and adopted by modern industries. With years of experiments and improvements, it can basically meet the monitoring needs of the operating conditions of rotating machinery and equipment in a simple environment. Wired connections have the advantage of simultaneous real-time transmission of vibration signals and fast transmission of multiple channels. However, in some complex environments, it also reveals some deficiencies affecting the quality of monitoring of the system. For example, some auxiliary equipment such as fans, pumps and pumps in power plants are widely distributed. If the cable rotating machinery vibration monitoring system is adopted, the cost of the equipment is high. Therefore, the maintainability of the equipment is poor.

In order to solve the problem of vibration monitoring system of wired rotating machinery in some special circumstances, a new method of monitoring mechanical vibration based on wireless sensor networks (WSN) is proposed. The emergence of this new monitoring solution is due to the rapid development of embedded systems, wireless networks and integrated hardware circuits in recent decades. It reduces the cost and power consumption of wireless sensor network and breaks through the development barrier of wireless sensor network. Wireless sensor network monitoring mode is a novel technique for obtaining vibration signals. Through a large number of distributed sensor nodes self-organizing method, a wireless data transmission mode is constructed, to make up for the deficiencies of the traditional wired monitoring system in some special cases. In this paper, the new monitoring method is mainly studied.

2 State of the art

The research of wireless sensor networks originated from the research projects of the United States military. With the further research on wireless sensor networks, the application of wireless sensor networks has begun to expand in industry, agriculture, transportation and medical care, especially in industrial vibration monitoring. Many foreign scientific research institutions and university laboratories have also begun to invest a lot of time and money on the wireless sensor network hardware circuit design and software system improvements. Branch J. et al. [1] studied the detection of outliers in the wireless sensor networks. Fan X. and Song Y. [2] improved the LEACH protocol for wireless sensor networks. Some of the notable accomplishments include the UC / Berkeley WINs Laboratory and the State Cleveland University Mobile Computing Laboratory. Gutierrez J. et al. [3] proposed an automatic irrigation system based on wireless sensor networks and GPRS modules. In China, Chinese Academy of Sciences software institute, Ningbo Institute of Chinese Academy of Sciences, Wuhan University of Technology, Chongqing University, Xi'an Jiao Tong University, Taiyuan University of Technology and other famous universities first launched research on wireless sensor network.

In the field of industrial vibration monitoring, the research difficulties of wireless sensor networks mainly focus on the monitoring nodes, especially the hardware design of monitoring nodes and the wireless communication protocol between nodes. Han Z. et al. [4] proposed a generic self-organizing tree energy balance routing protocol based on wireless sensor networks. From the node hardware structure design, the current study of the node can be divided into two kinds: one is a discrete component-based design method; the other is based on the integrated system approach. In order to control node cost and node composability, most existing nodes are designed based on the method of discrete components. Jelicic V. et al. [5] pointed out that the hardware of the node is generally welded on the printed circuit board by the basic structure of the sensor, the central processor, the data memory, the radio frequency component and the power supply unit. Liu Y. et al. [6] pointed out that the selection of these devices can determine the performance, power and life of the nodes. The computing power of the node is determined by the core processor. Nasser N. et al. [7] designed a dynamic multi-level priority packet scheduling scheme for wireless sensor networks. Neha J. and Dharma PA. [8] thought that the performance of data storage is determined by the capacity of the memory and the reading and writing rate. Visser H.J. and Vullers [9] studied RF energy collection and transmission in wireless sensor network applications. The radio frequency communication module of the node determines the rate and distance of the wireless transmission. The service life of the node is determined by the power supply unit.

In the field of mechanical vibration monitoring, high frequency signal collection, high-precision data acquisition, data storage and reliable transmission, and energy supply of wireless sensor network are studied. Villas L. et al. [10] proposed a lightweight and reliable routing method for intra-network aggregation in wireless sensor networks. The existing monitoring system is difficult to meet the monitoring requirements of some rotating machinery vibration. A monitoring system including wireless sensor network node, base station and PC software is designed, to achieve the collection, uploading, preservation and analysis of vibration signals of rotating machinery. The network topology and wireless communication protocol are studied. A complete wireless sensor network rotating machinery vibration monitoring system is formed.

To sum up, the existing monitoring system is difficult to meet the monitoring requirements of some rotating machinery vibration. To solve the problem of vibration monitoring system of wired rotating machinery in some special circumstances, a new method of monitoring mechanical vibration based on wireless sensor networks (WSN) is proposed. It reduces the cost and power consumption of wireless sensor network and breaks through the development barrier of wireless sensor network. Wireless sensor network monitoring mode is a novel technique for obtaining vibration signals. Through a large number of distributed sensor nodes self-organizing method, a wireless data transmission mode is constructed, to make up for the deficiencies of the traditional wired monitoring system in some special cases.

3 Methodology

3.1 Hardware design of wireless monitoring system for rotating machinery

Through the design and analysis of the platform, the overall structure of the system is mainly composed of three parts: wireless sensor network monitoring node, wireless sensor network monitoring base station and wireless sensor network host computer monitoring software.

The wireless rotating machinery vibration monitoring node uses the 32-bit processor STM32F405RG of the Cortex-M4 kernel of ST company as the core processor of the monitoring node. Radio frequency takes SiliconLabs Si4463 as the core, and equipped with AnalogDevices high-precision 16bits A / D converter and MEMS acceleration sensor as the signal acquisition front-end. In addition, high-capacity Flash memory modules and high-efficiency power modules are used as an aid. Rotating machinery vibration monitoring requires higher accuracy and sampling rate. During the monitoring process, a large amount of data is generated. In view of the large power consumption problems of data storage, computing and RF data transmission caused by large amount of data, the designed monitoring nodes must have higher computing power, lower energy consumption and superior storage capacity. The overall design scheme of the wireless rotating machinery vibration monitoring node is shown in Figure 1.

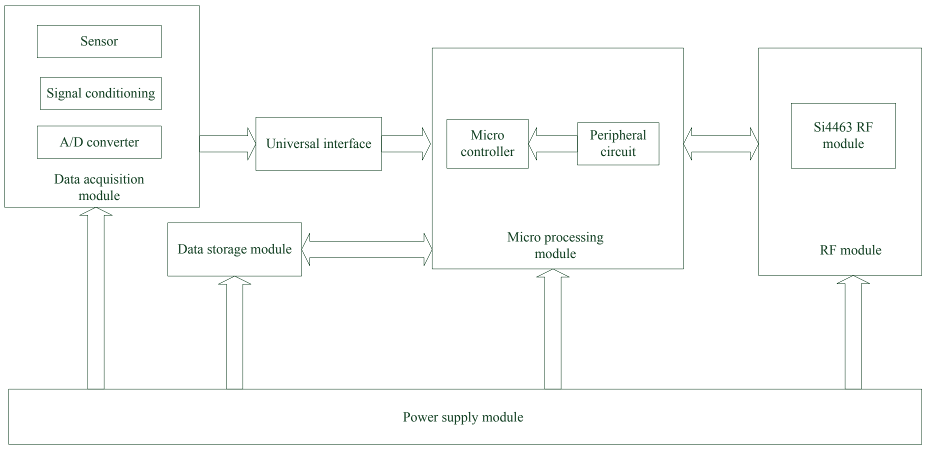

Fig. 1. The overall design scheme of the wireless rotating machinery vibration monitoring node

The processor is the key point in the design of the whole monitoring node. The microprocessor of the monitoring node uses the 32-bit microprocessor STM32F405RG based on the ARMCortex-M4 core architecture. The maximum operating frequency is 168MHz. It can achieve 210DMIPS (Million Instructions executed Per Second) computing performance. STM32F405 microcontroller also integrates up to 1M bytes of programmable Flash and 192kb of SRAM, which is sufficient to meet the monitoring node data processing basic requirements. In addition, STM32F405 microprocessor also has a rich external device interface. Three Serial Peripheral Interfaces (SPIs) enable half-duplex or full-duplex synchronous serial communication with external devices. Six Universal Synchronous Asynchronous Receiver Transmitters (USARTs) provide full duplex data exchange with external devices. However, the STM32F405 microprocessor has ultralow power consumption. It starts with the MCU core voltage and the peripheral driving voltage. The MCU core voltage design is only 1.2V, and the peripheral driving voltage is reduced to 1.7V. ART Acceleration reduces the latency of Flash memory access. In standby mode, power consumption is only 1μA

(RTC clock power supply), and 4kbSRAM power supply is only 2μA. The node processor structure and resource allocation are shown in Figure 2.

The sensing part needs to measure the vibration parameters of the equipment. The sensor module has the characteristics of small size, low power consumption and simple circuit. The frequency components of mechanical vibration are related to the specific mechanical structure. The vibration signals of a typical mechanical structure often contain a rich frequency component from tens of hertz to thousands of Hertz. Therefore, the vibration sensor has large bandwidth. The node adopts the high-performance MEMS vibration acceleration sensor ADXL22035 of ADI company. The schematic diagram of the peripheral circuit of the acceleration sensor is shown in Figure 3.

In order to meet the requirements of analog signal acquisition accuracy and sampling rate for the system design, the A/D of the A/D conversion part of the project adopts the independent A/D converter AD7685 of ADI company. It features sampling

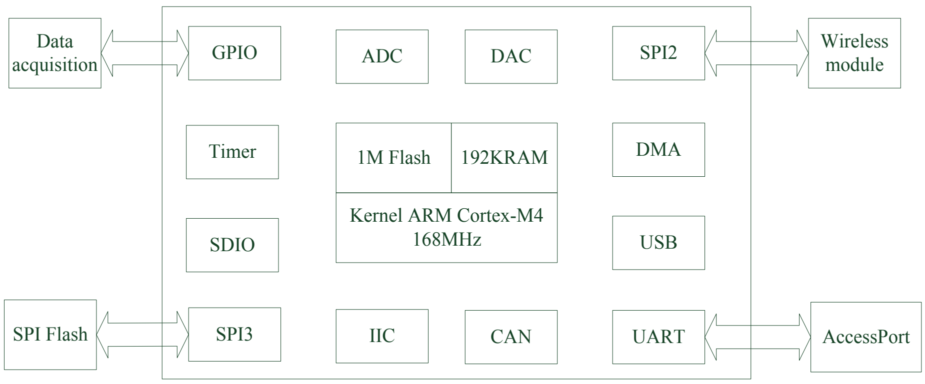

Fig. 2. The node processor structure and resource allocation

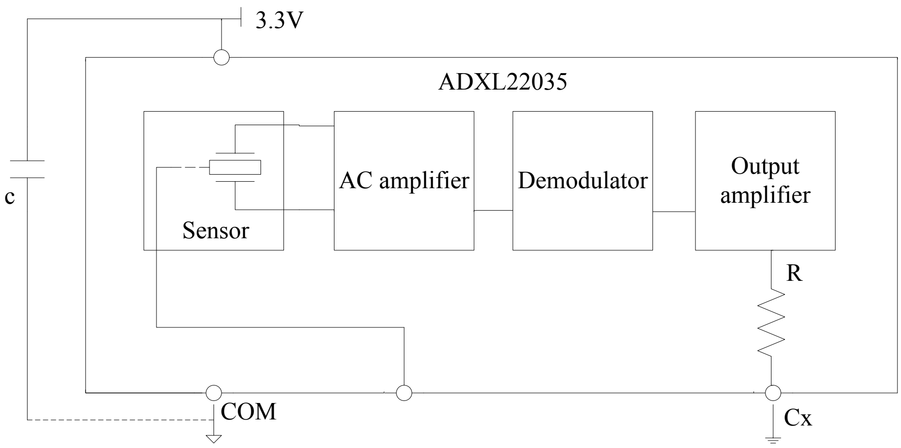

Fig. 3. The schematic diagram of the peripheral circuit of the acceleration sensor

rates up to 250kSPS at 16-bit conversion accuracy, 93.5dB SINAD, and a single 2.3V to 5.5V supply. At 3.3V supply voltage and 200kSPS sampling rate, the power dissipation is 1.5mW. In standby mode, the current can be as low as 1nA, which is ideal for battery-powered systems with limited power supply.

High speed and high precision vibration signals of rotating machinery have the characteristics of mass and high speed. On the contrary, the transmission rate of wireless network is difficult to achieve real-time transmission requirements, so rotating machinery vibration monitoring nodes must have a larger data storage space and faster read and write access speed memory. The existing wireless sensor network nodes, because of the slow variable signals or low frequency signals, most of which have no extended memory. The maximum design sampling rate of the monitoring node is 10kHz, and the resolution of the A/D converter is 16 bits. At the maximum sampling rate, the vibration data of 20kBytes will be generated per second. If the monitoring node is collected at the maximum sampling rate for one minute, the vibration data of 1.2Mbytes will be generated. Monitoring nodes must be able to collect data in one minute without storing storage space, which means that the collected data is overflowing. The continuous writing speed of the memory of the monitoring node must be greater than 20kB/s, and the storage space must be more than 1.2MBytes. The memory parts of the monitoring node use the serial NOR Flash chip SST25VF016B of Microchip as the data storage medium. The memory has a wide power supply range of 2.7V~3.6V, a storage space of 2 megabytes, a clock frequency of 80MHz, an ultra-low standby current of 5uA, and a four wire compatible SPI interfaces. Thus, the low pin number package, which takes up less circuit board space, is very suitable for the battery power supply system with limited power supply. The microprocessor of the monitoring node uses the STM32F405RG of the ARMCorte-M4 kernel with rich peripherals. It has three SPI interfaces and can read and write SPI_Flash at high speed in the way of DMA.

The base station node in the vibration monitoring of the rotating machinery is used as the data transfer station for multiple monitoring nodes. Therefore, a large number of monitoring data from each monitoring node will be converged to the base station node. Aiming at the problem of data storage and operation performance caused by a large number of monitoring data aggregation, the designed base station nodes must have strong computing performance and outstanding data storage capacity. Base station nodes do not have wiring restrictions or other difficulties. Therefore, base stations with high power consumption have adopted power-limited wired mode without power supply. The overall design scheme of the wireless rotating machinery vibration base station node is shown in Figure 4. The node of the base station consists of five parts: control center, data storage, radio frequency transmission, Ethernet communication and power supply and power supply. The design adopts the modular concept, which is beneficial to the addition and deletion of different functional modules, increases the flexibility of the equipment, and facilitates the upgrading and transformation of the equipment.

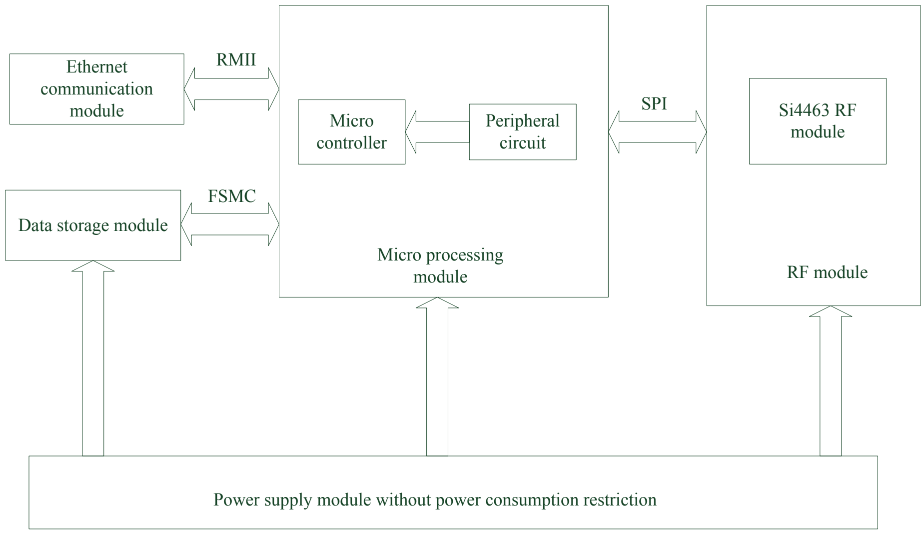

Fig. 4. The overall design scheme of the wireless rotating machinery vibration base station node

High-frequency signals for rotating machinery must use a higher sampling rate. Therefore, monitoring nodes will produce a large number of monitoring data. The base station node needs to converge the monitoring data of multiple monitoring nodes to the host computer. In order to avoid data overflow, a read and write speed and no memory erasing limit should be chosen as the monitoring data storage medium. The memory is divided into internal memory and external memory. The internal memory is integrated inside the microprocessor. The external memory includes SRAM, FLASH, and SD cards. The difference between SRAM and other memory is shown in Table 1.

Table 1. The difference between SRAM and other memory

Memory	Characteristics
SRAM	Fast speed, high efficiency, low power consumption, no erase limit, no need to refresh the circuit
FALSH	Large capacity, low cost, slow, erase the number of restrictions
SD	Large capacity, low cost, slow reading and writing, difficult operation

The CMOS static storage chip IS62WV102416 produced by ISSI company is used as the data storage unit. Figure 5 is a schematic diagram of a typical application circuit for a high-speed data storage module. STM32F407 processor comes with FSMC (Flexible Static Memory Controller) bus interface, which supports SRAM, NANDFLASH, NORFLASH and PSRAM memory.

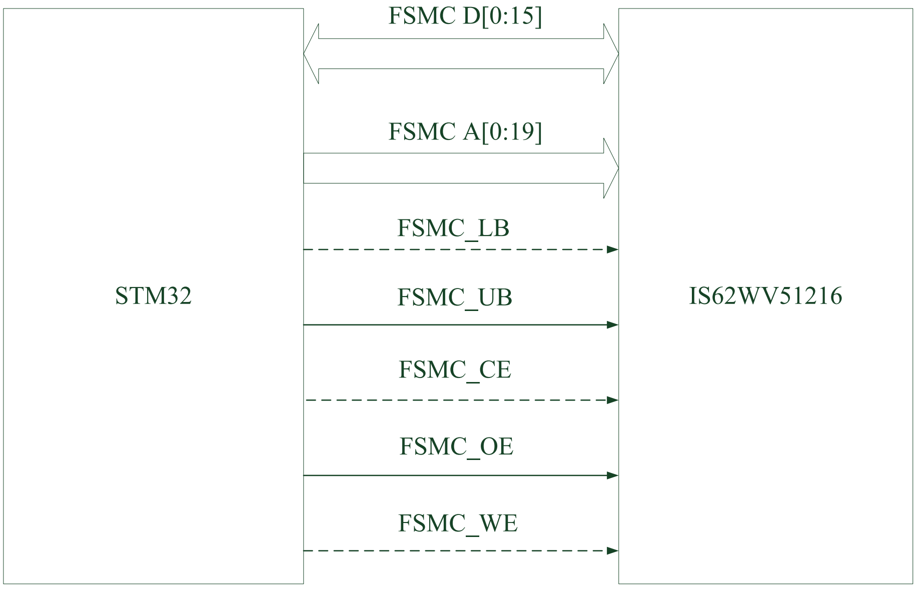

Fig. 5. High-speed data storage module of the typical application circuit diagram

3.2 Software design of wireless monitoring system for rotating machinery

Figure 6 is an overall plan for monitoring software. The monitoring node is responsible for vibration data acquisition, storage and radio frequency transmission. The base station node is responsible for network maintenance as well as data reception, storage and uploading. PC is responsible for receiving the monitoring data in real time display, storage and data playback and other functions.

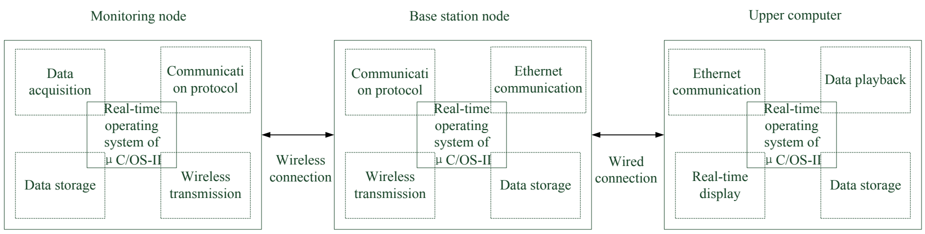

Fig. 6. The overall plan of monitoring software design

The stable, simple structure and multi task embedded real-time operating system μC/OS-II are adopted because of the multiple tasks performed by the nodes. The operating system schedules the system interrupts and tasks. As long as the function is added to the task, the operating system provides a management mechanism to coordinate the sharing of resources, to ensure the smooth running of the system. In this system, the monitoring node is the source of the entire network data. When the target node receives the acquisition command request information from the network or the current node sleeps, the monitoring node enters the data acquisition mode and acquires the vibration information of the current monitoring position and stores the vibration information. After the acquisition is complete, the wireless module starts to detect the current network status. When it is found that the network is idle, it starts to transmit the monitoring data to the base station node. The base station node is the data transfer station of the monitoring system. After receiving the monitoring data from the monitoring node, the base station node sends the data to the PC through the Ethernet port. The PC machine receives the data frame transmitted from the Ethernet port and analyzes the data frame. The data sent from different monitoring nodes are respectively placed into different data tables and displayed and stored, so as to realize the monitoring of the mechanical status. In addition, the program runs from different hardware platforms. The program can be divided into embedded software systems and user software systems. Among them, the embedded software system runs on the monitoring node and the base station node, which is written in C language. The user software system runs on the PC machine, which is developed in the Visual Basic language.

A well-performing system must not only be based on high-profile hardware, but also have a well-designed, compact, high-performance piece of software to give full play to the hardware's performance. Node software is written in the most widely used C language. The program is divided into blocks to simplify the difficulty of software design and improve the readability of the software. It is convenient for later modification and functional additions. The block diagram of the node software system is shown in Figure 7. After initializing the system in the main function, the primary task can be created and the other subtasks are created in the main task. Initialization function mainly sets up device resources, including initialization of I/O port, initialization of analog-to-digital converter, initialization of serial interface, initialization of radio frequency chip and initialization of μC/OS-II. The data acquisition function mainly realizes the collection of vibration signals, the conversion of modulus and data, and the storage of data. The radio frequency communication function mainly realizes the radio frequency transmission between nodes, and the interface drive function mainly completes data transmission between different devices.

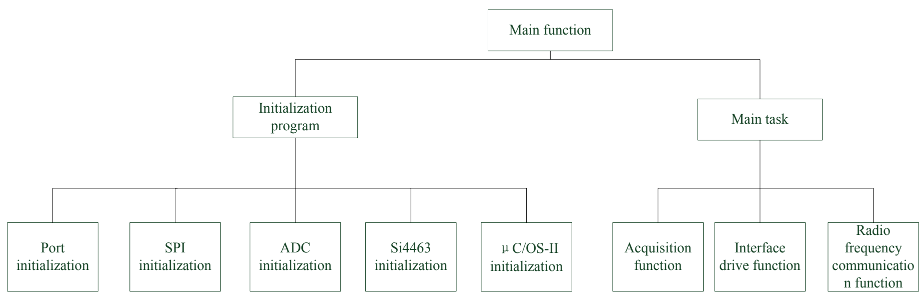

Fig. 7. Block diagram of node software system

4 Result Analysis and Discussion

4.1 Data reliable transmission test

After the sensor is collected and converted to digital by A/D, the data of the monitor interface is obtained. These data also need wireless transmission, data storage and wired transmission to arrive at the host computer monitoring interface. Therefore, data transmission is also an important link to ensure data reliability. First, the program of the monitoring node is modified, so that A/D is in a dormant state. A set of data that is monitored in the experiment is written in the FLASH memory. Then, the base station nodes are connected to the upper computer through the network line to connect the power supply, and the IP address of the host server is modified as "192.168.24.1". Finally, the host computer software is opened, the configuration parameters are modified and the node network state is observed, to ensure the success of the connection. When the "start" button is clicked on the monitor interface, the computer starts data transmission. When the monitoring node, the base station node and the upper computer connect successfully, the node on the network topology panel of the upper computer monitoring interface will be illuminated. After the connection between the monitoring node and the base station node is successful, the command control area and the waveform control area are selected for the appropriate parameters. Then, the "start transmission" button on the machine's software interface is clicked on by the mechanical vibration monitoring. After data transmission, the monitoring panel data area begins to display the received data. The waveform area of the monitor panel begins to display the received data and waveform. After 10 consecutive data transmission tests, the data received and stored in the data area are compared with the transmitted data and the data loss rate is calculated. The experimental results of Table 2 show that the monitoring data can meet the requirements of mechanical vibration monitoring during the wireless transmission process.

Table 2. Performance test for data transmission

Number	The length of the data sent	The length of the data received	Loss rate	Number
1	16384	16368	0.097%	1
2	16384	16352	0.195%	2
3	16384	16368	0.097%	3
4	16384	16368	0.097%	4
5	16384	16368	0.097%	5
6	16384	16368	0.097%	6
7	16384	16352	0.195%	7
8	16384	16368	0.097%	8
9	16384	16368	0.097%	9
10	16384	16368	0.097%	10

4.2 Comparison test of system performance

The ADXL22035 bandwidth of the high-performance MEMS acceleration sensor selected by the node is 2.5kHz, and the range is up to + 18G. A group of contrast tests were designed. Through the experimental data, whether the sensor meets the requirements of the vibration signal acquisition of the rotating machinery is evaluated. In order to verify the validity of node acquisition, Fourier transform of wired monitoring and data collected by wireless monitoring is carried out, and time domain signal is transformed into frequency domain to analyze. The main spectral lines are compared as shown in Table 3.

Table 3. Comparison of main spectral lines

YD-82 type sensor		**Monitoring node**	
Spectral line /Hz	***Voltage /mV***	***Spectral line /Hz***	***Voltage /mV***
81.79	915.8	81.79	915.8
163.6	135.6	163.6	135.6
245.4	272.7	245.4	272.7
322.9	83.14	322.9	83.14

As can be seen from Table 3, the main spectral line frequency is basically the same, the amplitude is relatively close. However, the amplitude of the monitoring node is generally smaller than that of the YD-82 sensor, which is mainly due to the installation error of the sensor and the deviation of the sensitive axis. The monitoring system designed in this paper can meet the needs of mechanical vibration monitoring.

5 Conclusions

By analyzing the application of wireless sensor network in the monitoring of mechanical vibration, a set of wireless sensor network vibration monitoring system suitable for rotating machinery is designed. It has preliminarily realized the monitoring of the state of mechanical equipment. Specifically, the main contents and contributions of this paper are as follows:

(1) A vibration monitoring platform for wireless sensor network is designed for rotating machinery. According to the design requirements, the hardware circuit design of the module units, such as data acquisition, data storage, wireless communication and power supply unit, is realized. In addition, the hardware circuit design of the module of data storage, wireless communication and wired communication of base station nodes is realized. The welding debugging of the hardware is completed.

(2) The corresponding software design is completed on the prototype of the wireless sensor network monitoring platform of the rotating machinery. The basic debugging and verification of the wireless sensor network monitoring platform for the vibration of rotating machinery is carried out. Through the data transmission experiment, the reliability of the data in the transmission process is verified.

(3) By comparing with the traditional cable vibration sensor, the performance of the monitoring system is verified. The test results show that the wireless vibration monitoring system designed in this paper can meet the requirements of the monitoring of the vibration state of the rotating machinery. The wireless vibration monitoring of rotating machinery has been realized preliminarily.

6 References

[1] Branch J, Szymanski B, Giannella C, et al. In-Network Outlier Detection in Wireless Sensor Networks: Knowledge & Information Systems, 2013, vol. 34, pp. 23-54. https://doi.org/10.1007/s10115-011-0474-5
[2] Fan X, Song Y. Improvement on LEACH Protocol of Wireless Sensor Network: Applied Mechanics & Materials, 2013, vol. 347(350), pp. 1738-1742.
[3] Gutierrez J, Villa-Medina JF, Nieto-Garibay A, et al. Automated Irrigation System Using a Wireless Sensor Network and GPRS Module: IEEE Transactions on Instrumentation & Measurement, 2013, vol. 63(1), pp. 166-176. https://doi.org/10.1109/TIM.2013.2276487
[4] Han Z, Wu J, Zhang J, et al. A General Self-Organized Tree-Based Energy-Balance Routing Protocol for Wireless Sensor Network: IEEE Transactions on Nuclear Science, 2014, vol. 61(2), pp. 732-740. https://doi.org/10.1109/TNS.2014.2309351
[5] Jelicic V, Magno M, Brunelli D, et al. Context-Adaptive Multimodal Wireless Sensor Network for Energy-Efficient Gas Monitoring: IEEE Sensors Journal, 2013, vol. 13(1), pp. 328-338. https://doi.org/10.1109/JSEN.2012.2215733
[6] Liu Y, He Y, Li M, et al. Does Wireless Sensor Network Scale? A Measurement Study on GreenOrbs: IEEE Transactions on Parallel & Distributed Systems, 2014, vol. 24(10), pp. 1983-1993. https://doi.org/10.1109/TPDS.2012.216
[7] Nasser N, Karim L, Taleb T. Dynamic Multilevel Priority Packet Scheduling Scheme for Wireless Sensor Network: IEEE Transactions on Wireless Communications, 2013, pvol. 12(4), pp. 1448-1459.
[8] Neha J, Dharma PA. Current Trends in Wireless Sensor Network Design: International Journal of Distributed Sensor Networks, 2014, vol. 1, pp. 101-122.
[9] Visser HJ, Vullers RJM. RF Energy Harvesting and Transport for Wireless Sensor Network Applications: Principles and Requirements: Proceedings of the IEEE, 2013, vol. 101, pp. 1410-1423. https://doi.org/10.1109/JPROC.2013.2250891
[10] Villas L, Boukerche A, Filho HSR, et al. DRINA: A Lightweight and Reliable Routing Approach for In-Network Aggregation in Wireless Sensor Networks: IEEE Transactions on Computers, 2013, vol. 62(4), pp. 676-689. https://doi.org/10.1109/TC.2012.31

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