İSTANBUL UNIVERSITY CERRAHPAŞA

ORIGINAL ARTICLE
Electrica 2022; 22(3): 428-437

Vibration State Monitoring of Mechanical Equipment Based on Wireless Sensor Network Technology

Yuhua Peng[1], Ying Wang[2], R. Raffik[3], Vishal Jagota[4], Komal Kumar Bhatia[5], Ravi Kumar[6], Nithiyananthan Kannan[7]

[1]Wuchang University of Technology Artificial Intelligence School, HuBei, China
[2]School of Mechanical Engineering, Wuhan Polytechnic University, HuBei, China
[3]Department of Mechatronics Engineering, Kumaraguru College of Technology, Coimbatore, Tamilnadu, India
[4]Department of Mechanical Engineering, Madanapalle Institute of Technology & Science, Madanapalle, AP, India
[5]Department of Computer Engineering, J.C. Bose University of Science & Technology, ertwhile YMCA University of Science & Technology, Faridabad, Haryana, India
[6]Department of Electronics and Communication Engineering, Jaypee University of Engineering and Technology, Guna, Madhya Pradesh, India
[7]Department of Electrical Engineering, Faculty of Engineering, Rabigh King Abdulaziz University, Jeddah, Saudi Arabia

Cite this article as: Y. Peng, et al. "Vibration state monitoring of mechanical equipment based on wireless sensor network technology," *Electrica*, 22(3), 428-437, 2022.

ABSTRACT

In recent years, my country's smart grid has developed rapidly and is safe and stable operation of the power grid system; it is related to the healthy development of the national economy and stable life of the people. Most of the current vibration monitoring systems use wired ICP piezoelectric acceleration sensors to collect the vibration of the transformer tank wall, on-site live monitoring, and safety, but there are many inconveniences and problems. The author designed a vibration-sensing element based on the latest Micro-electromechanical systems (MEMS), a vibration sensor for wireless communication with ZigBee, applied in the online monitoring of a 110 kV three-phase power transformer in operation, and adopted wired and wireless sensor modes, respectively, to monitor and compare waveforms. The wired sensor used in the test is an ICP sensor, and its sensitivity is 500 mV/g. It can be used in a multi-vibration measuring point wireless network to monitor the surface vibration of the power transformer tank. In the waveform graph collected by wireless sensor, it can be observed that the waveform presents a periodic law, and it can be observed from the spectrogram that the energy is concentrated on the frequency multiplier of 50 Hz, which conforms to the vibration law of the transformer.
Index Terms—Condition monitoring, power transformer, vibration analysis method, wireless sensing, ZigBee.

I. INTRODUCTION

The internet of energy is the only way to encourage the co-construction, co-financing, and sharing of electric energy, as well the intelligent upgrading of the electric power industry. It has emerged as the concentrate of the growth of various countries around the world in the new round of worldwide technological advancement and industrialization [1]. As the economics and technology of my nation have advanced so quickly in recent years, building intelligent substations has drawn a lot of study interest. Higher security standards are demanded due to the growing number of innovative applications, which encourage a significant increase in the number of information collection points and the volume of information collected by the power communication system [2]. Mechanical vibration detection for spinning heavy machinery can help to improve the safety overall, depending on the equipment. Standard cable monitoring solutions have challenges with maximum signal pickup and greater data collection [3, 4]. As the hub of smart grid energy transmission, substations, its operational reliability directly affects the stable and reliable supply of electricity, power equipment, as its basic element, are the basis for ensuring the reliability of power supply. In substations, main power equipment such as transformers, circuit breakers, and switch cabinets, complicated physical or chemical changes occur inside due to the surrounding environment, electrical, thermal, mechanical, load, and other factors, causing the insulating material to deteriorate, equipment to wear out, performance degradation, and in severe cases, it can cause power equipment to malfunction, thereby affecting the safe and reliable operation of the power grid [5]. The mechanical vibration signals obtained from sensors are analyzed by the vibration fault surveillance system. This approach is used to identify and detect medical damage to equipment or to forecast future mechanical equipment failure trends [6, 7]. The section defines a vibration sensor module based on the most recent MEMS, a vibration

Corresponding author:
Vishal Jagota

E-mail: vishaljagota@mits.ac.in

Received: May 11, 2022

Revised: August 2, 2022

Accepted: August 15, 2022

Publication Date: September 26, 2022

DOI: 10.5152/electrica.2022.22051

sensor for wireless connectivity with ZigBee, used in the online monitoring of an operating 110 kV three-phase power transformer, and adopted wired and wireless sensor modes, respectively, to monitor and compare waveforms. ICP sensors with a sensitivity of 500 mV/g were employed as the wired sensors in the test. It can be utilized in a wireless network with several vibration measuring points to track the surface vibration of the power transformer tank.

II. LITERATURE REVIEW

The state of rolling bearings has a considerable influence on mechanical equipment's performance. When a rolling bearing fails, it diminishes the long-term stability of the industrial devices and lowers productivity and that may result in a serious industrial catastrophe as the industrial sector has higher and higher requirements for improving production [8, 9]. The base station's primary job is to collect, organize, and pack the data gathered by the wireless sensor network's nodes before sending the data. Efficiency and product quality, reducing energy consumption and environmental pollution, and the demand for intelligent industrial monitoring and control systems are becoming increasingly urgent, especially low-cost wireless industrial intelligent systems. As early as 2004, the US Department of Energy, General Electric Global Research Institute, Sensicast Company, and Rensselaer Institute of Technology began to collaborate to improve motor efficiency, reduce energy consumption, reduce the cost of building a motor monitoring system, promote energy saving, and high efficiency of the entire industrial motor system. Crossbow, and Intel Corporation launched a Loch Rannoch project in 2004, using Mote nodes and 150 acceleration sensors, to monitor equipment with strong vibrations such as tanker motors and pumps. Gierlak, P. et al. discussed the advantages and disadvantages of wireless industrial bus systems [10]. The mechanical equipment status surveillance system is crucial for real-time monitoring of component operating state [11, 12]. Romeo-Gabriel, M. et al. studied the application of wireless communication technology in power automation systems, and it is the first time to discuss the requirements and constraints faced by Industrial Wireless Sensor Networks in terms of hardware and software and analyze the opportunities and challenges of industrial wireless sensor networks in the next-generation power system [13]. Industrial wireless sensor network, as a special type of wireless sensor network, plays a vital role in the construction of highly reliable, self-repairing, and high-efficiency industrial systems and has received more and more attention from researchers, for example, IEEE Transactions on Industrial Informatics, an authoritative academic journal of industrial information, used it in 2009 and 2014 and carried out a special discussion on industrial wireless sensor networks. In terms of routing research in industrial wireless sensor networks, Ambika, P. S. et al. introduced the Two-Hop Velocity Based Routing (THVR) algorithm in a wireless sensor network based on gradient routing [14], while ensuring energy efficiency and improving the real-time performance of network transmission; Nasir, V. et al. proposed a multi-channel superframe scheduling algorithm [15], to ensure the connectivity of all clusters while avoiding beacon conflicts; Liu, J. P. et al. aimed at the problem of network communication energy consumption, proposed an energy-balanced routing method (FAF-EBRM) based on frontal perception parameters, and selected the next hop node according to the link weight and energy density, and it also includes a spontaneous local topology reconstruction mechanism [16]. Compared to other experimental characteristics, vibration signals are simpler to gather and have a higher degree of accuracy for indicating whether a bearing is operating normally or improperly. As a result, vibration signal analysis is applied in the majority of mechanical situation detection techniques [17, 18]. In response to the problem of reliable data transmission in industrial wireless sensor networks, Yi, L. I. et al. proposed a reliable reactive enhanced routing (R3E) to improve the resilience of the link after dynamic changes [19]; Cheng, A. L. et al. aimed at the problem of key information transmission in the network and proposed a Media access control (MAC) protocol with priority scheduling capability (PriorityMAC) [20]; Chen, J. et al. used transmission power control to solve the problems of wireless network communication energy consumption, interference, and attenuation [21]; Miao, Y. et al. aimed at the problem of vibration energy collection and researched a winding low-frequency piezoelectric vibration energy harvester [22]; and Fu, S. et al. designed a wireless sensor network state monitoring system driven by it [23].

In response to a number of problems with wired revolving commercial vibration surveillance systems under specific climate factors, the development of wireless sensor networks has entered people's research fields [24, 25]. For the control of VLC dimming, polar codes with RLL line codes and compensating symbols were used. While possible measure was suggested as a way to reduce the code length, the RLL codes still resulted in low transmission capacity [26]. The multirate traffic is made easier by the OVSF codes. This is due to the variety of spreading factor choices. The Walsh functions are used to produce the OVSF codes. Calls are handled at varying rates by the codes with various spreading factors. All of a code's ancestors and descendants are forbidden from being assigned, which is one of the key characteristics of OVSF codes. Assigning complementary codes to each new call is necessary. The frequency of the call that an OVSF code can support is determined by the SF of the code. The higher is SF, the lower code's location in the tree, and likewise. All ancestors and descendants of a code that has been allocated are blocked. It restricts the assortment of OVSF codes. OVSF codes should therefore be distributed effectively [27, 28]. Non-orthogonal multiple access, which permits some interruption at receivers, emerges as a remedy to overhaul the huge performance issue. Relays have recently been used to increase access for cell edge users. Relay use increases spectrum efficiency while lowering the likelihood of outages. The relays employed in this study are capable of successive interference cancellation for the users connected to it, and they solely renew the signals of those users. When there are several relays offered and the user chooses the link with the best channel quality, the cell edge users can communicate with the access point [29]. The five primary parts of a wireless sensor network monitoring node are the control center, data gathering, data storage, radio frequency transmission, and power supply [30, 31]. The normal or defective state of bearings during operation can be better characterized by vibration signals than by other physical qualities. Because of this, vibration signal analysis-based mechanical condition detection systems are the most popular [32]. Mechanical equipment status monitoring systems with wired connections are used in a variety of large-scale equipment detection and critical process purposes [33]. Vibration fault monitoring system uses the analysis of the mechanical vibration signals gathered by the sensors to determine the condition of the local or overall mechanical components during operation. This technique is used to identify mechanical equipment failures before they occur or to foresee how failures of mechanical equipment will develop [34]. Numerous spinning mechanical structures are frequently seen in contemporary large-scale electro-mechanical equipment. The most popular and essential component in rotating equipment is the rolling bearing

[35]. The state of operation of all mechanical equipment is significantly impacted by the rolling bearings' condition [36]. When a rolling bearing malfunctions, it immediately lowers the stability of all mechanical equipment, lowers operating efficiency, and may even result in a major manufacturing accident [37].

It can be seen from the above research that machine condition monitoring system based on wireless sensor network has great application prospects, as shown in Fig. 1, use wireless network communication, can make up for some of the shortcomings of traditional wired communication methods, and it can form a distributed mechanical condition monitoring and fault diagnosis system. However, due to the limitation of the hardware performance of the sensor network itself, such as limited battery power, network bandwidth, processing power, etc., there are still some challenges and problems that need to be resolved.

III. METHODS

A. Hardware Design

The most common wireless connectivity technologies that are currently in use are Bluetooth, WiFi, ZigBee, and others; each has unique properties and can be used in a variety of communication contexts. The Bluetooth data transmission rate is the fastest among them, but it has the drawback of a small data packet size during transmission and a short communication range; WiFi has been very popular recently, while it offers convenient networking and a large transmission distance, its main drawback is significant power consumption. The ZigBee technique offers advantages over the ones mentioned before in terms of low power consumption, low cost, and strong networking capabilities, but it has drawbacks in terms of data transmission rate and time delay. Since the system needs to meet low power consumption, low cost, moderate communication distance requirements, it needs to have a certain degree of security. Compared with the above communication methods, ZigBee has the lowest power consumption, and at the same time, its transmission distance, transmission rate, cost, and safety meet the system requirements and have a powerful networking function [38, 39]. So, this design uses ZigBee's wireless communication method. In the choice of vibration acceleration sensor, the main consideration is when the sampling parameters are met, choose a solution with low power consumption and small size. SSelect MEMS-sensing element as a vibration collection element to miniaturise the entire sensor system and meet the demanding application scenarios of volume and space, while the digitised data read from the MEMS reduces

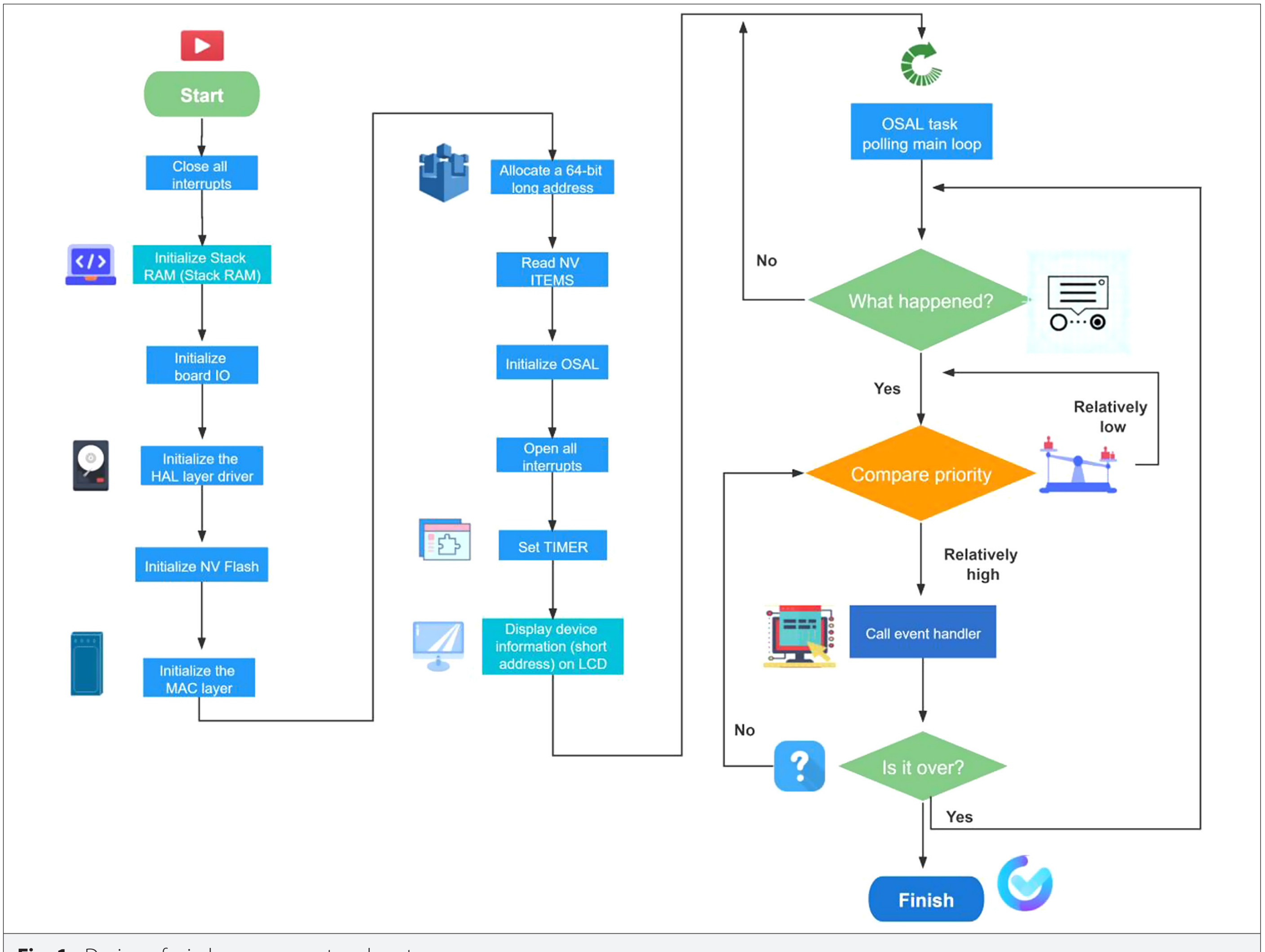

Fig. 1. Design of wireless sensor network system.

TABLE I. MAIN PERFORMANCE PARAMETERS OF ADIS16006

Vibration Range	Effective Digits	Resolution	Sampling Frequency	Bandwidth	Root Mean Square Error
+5 gn	3.9 mg/ISB	12 bit	10 kHz	2.26 kHz	11.9 mg

external interference and improves the sensor system's electromagnetic compatibility of the sensor system [40, 41]. According to the parameters, the final sensor model chosen is ADIS16006, which has low power consumption, a small size, and can meet the dual-axis acquisition characteristics. The specific parameters of the sensor are shown in Table I.

This design uses micro-power MEMS vibration-sensing elements, and ZigBee wireless module, to realize micro-power wireless vibration sensing, and it is suitable for multi-vibration measuring point nodes in the form of Internet of Things power transformer tank surface vibration monitoring program. The solution first collects vibration signals through each wireless vibration sensor, and the vibration signal is transmitted wirelessly to the transformer vibration status monitoring system (lower computer) for processing and storage, and finally, the processed data will be processed through network communication and sent to the client PC software (upper computer), for further data analysis and diagnosis [42-44].

The wireless sensor mainly includes two parts: the terminal and the coordinator. An acceleration sensor is integrated into the terminal, attached to the wall of the transformer tank when in use, and mainly responsible for signal collection and wireless transmission; it consists of a vibration sensor, a data processing control module, a wireless communication module, a serial communication module, and a power supply module. The coordinator is responsible for the reception and storage of signals, it is composed of data acquisition module, data processing control module, wireless communication module, and power supply module [45,46]. When collecting on-site, because of the need for a multi-signal acquisition matrix, set up multiple terminals for signal acquisition, as multiple terminals and coordinators form a wireless sensor network for signal transmission. The Yuxian sensor is composed of a meter set module, a data control module, a wireless communication module, and a power supply module, as shown in Fig. 2. The data acquisition module is an acceleration sensor ADIS16006 responsible for collecting node vibration data. The data processing control module mainly includes a microprocessor and memory, responsible for node control, node data processing, and storage. The wireless communication module is mainly composed of a wireless transceiver, responsible for the communication and transmission of control signals, acquisition signals, and other sensor node signals. The power module is responsible for the energy supply of the entire node.

The coordinator node is composed of a data processing control module, a wireless communication module, a serial port/SPI communication module, and a power supply module. Nine terminal devices placed on the transformer tank's wall will begin to collect simultaneously when the terminal module gets the collection start command broadcast by the coordinator. The design of the data processing control module, wireless communication module, and power supply module is similar to that of the terminal node, and hence repeated. Serial Peripheral Interface (SPI) communication module provides a means for communication between the microprocessor and the subsequent monitoring system.

B. Software Design

The software part of the design mainly realizes the collection, wireless transmission, and storage of vibration signals, and finally, through the interface, the collected signal is transmitted to the transformer vibration monitoring system. When the wired acquisition result is compared to the filtering result, the signal consistency is stronger, which is notably evident in the waveform graph. When choosing a vibration acceleration sensor, the important factor to take into account is that the solution should have a low power requirement and be compact. By choosing a MEMS-sensing element as the vibration collection element, the sensor system may be miniaturized to suit the demanding application situations for volume and space while also reducing external interference and enhancing electromagnetic compatibility. By forming a star network, nine terminal devices collect vibration acceleration signals and wirelessly transmit them to the coordinator, who is responsible for wireless signal reception, storage, and transmission to the monitoring system. Its overall function and architecture are shown in Fig. 3.

The realization of ZigBee wireless network is based on the ZigBee protocol stack. For CC2530, TI Company provides a complete Z-Stack protocol stack, and this protocol stack can realize the networking of complex networks. System initialization is to prepare for the operation of the operating system. It is mainly divided into initializing the system clock, detecting whether the chip voltage is normal, initializing the stack inside the chip, initializing the configuration of the hardware board, initializing the hardware modules of the chip, initializing the Flash storage, forming the node MAC address, initializing some non-volatile variables, initializing the MAC layer, initializing the application architecture layer, and initializing the operating system, and more than ten items such as all interrupts are enabled. The Operating system abstraction layer (OSAL) operating system entity starts with an infinite loop function: osal_start_system(). This

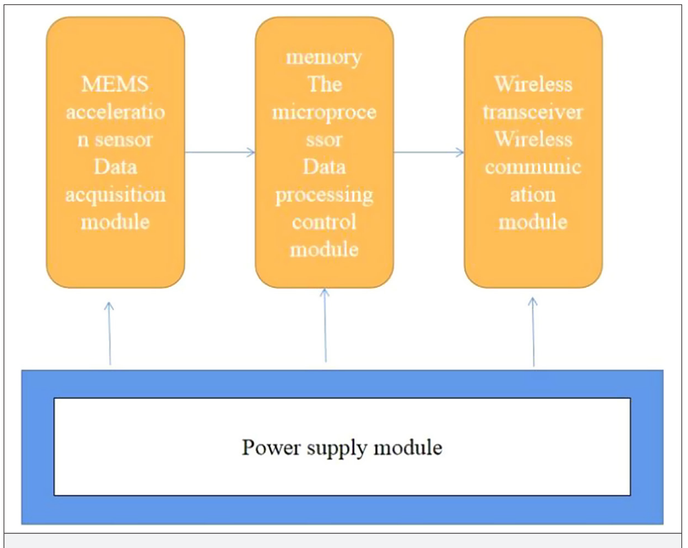

Fig. 2. Block diagram of terminal node module.

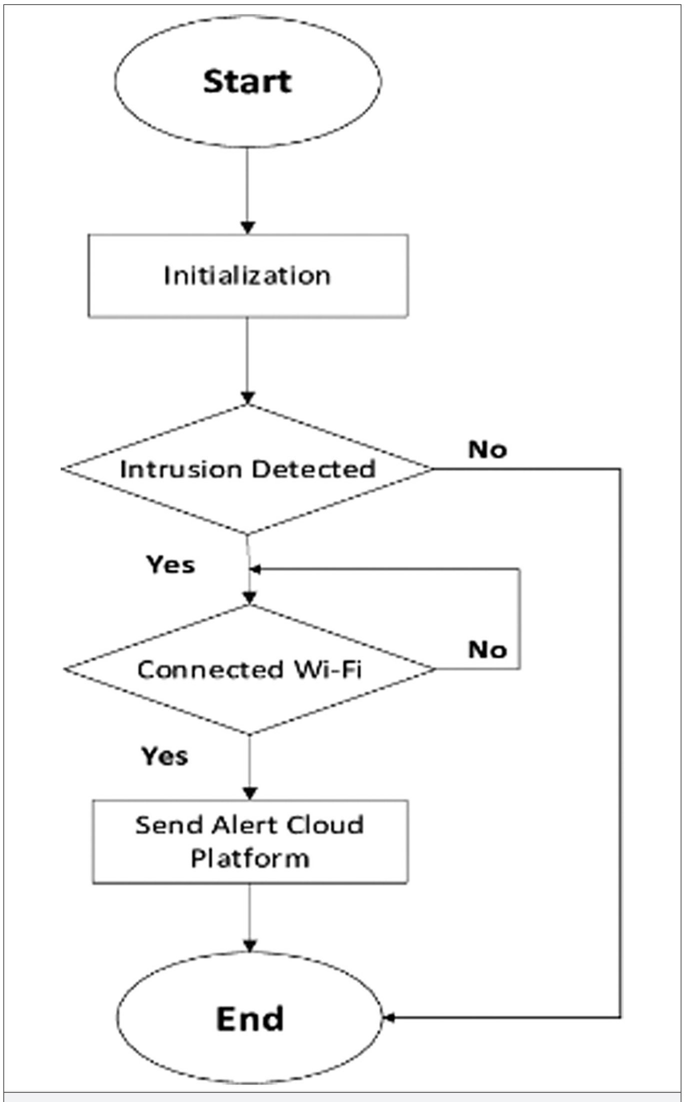

Fig. 3. Flow chart of wireless module work.

function is the main part of the rotating query operating system, and what it does is to constantly query whether an event has occurred in each task, if it happens, execute the corresponding function, if it does not happen, just query the next task. When developing the application layer, through the osalAddTasks () function, create OSAL tasks to run task programs. Data collection is an important part of the wireless module [47]. When the terminal module receives the collection start command broadcast by the coordinator, nine terminal devices arranged on the wall of the transformer tank start collecting simultaneously. Each terminal collects 1s of data according to the timer, a total of 8 000 bytes. After collecting for 1s, each terminal is preset according to the program and the data were sent wirelessly to the coordinator in turn [48].

TABLE II. SAMPLING RESULTS OF 2 GN VIBRATION INPUT SIGNAL AT DIFFERENT SWEEP FREQUENCIES

Sweep Frequency/Hz	40	80	160	500	1000	2000
Signal Amplitude/gn	2	2	1.95	1.95	1.9	1.8

TABLE III. SAMPLING RESULTS OF 0.5 GN VIBRATION INPUT SIGNAL UNDER DIFFERENT SWEEP FREQUENCIES

Sweep Frequency/Hz	40	80	160	1000
Signal Amplitude/gn	0.5	0.5	0.5	0.48

IV. RESULTS AND ANALYSIS

In transformer diagnosis based on vibration analysis, the frequency band of the vibration signal of concern is within 1000 Hz, and the vibration amplitude is 0.5–2 g. In order to verify the sampling performance of the wireless sensor in this frequency band and vibration amplitude, the test was carried out on a standard shaking table. When the peak-to-peak value of the input vibration signal is 2 gn and 0.5 gn respectively, set for different sweep frequencies and compared with the sampling output of the system, corresponding to different peak-to-peak values, under different sweep frequencies, the receiving end samples the signal amplitude, as shown in Tables II and III.

The waveform of the wireless receiving end is shown in Figs. 4 and 5.

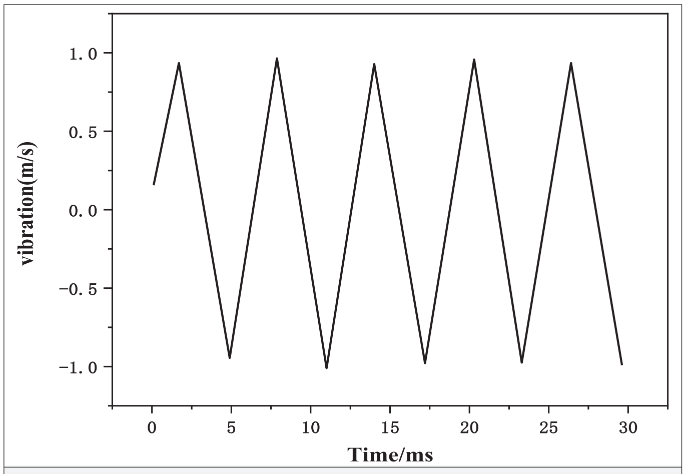

Fig. 4. The input signal is 160 Hz 2 gn receive waveform at peak.

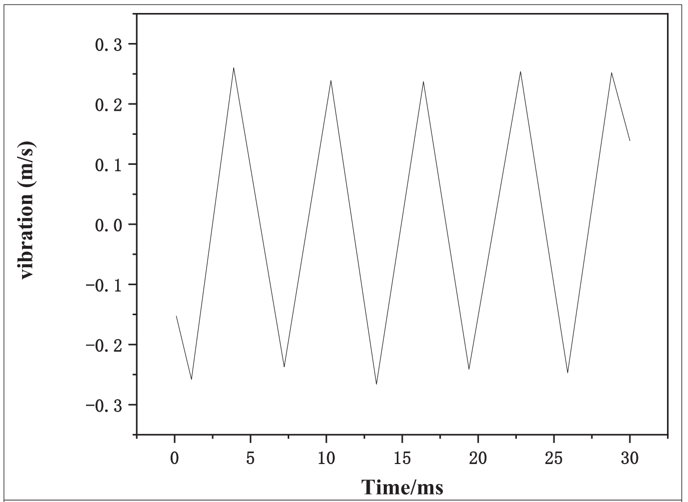

Fig. 5. The receiving waveform when the input signal is 160 Hz 0.5 gn peak-to-peak value.

It can be seen from the results of the table and waveform graph that when the frequency is not too high, the accuracy of the signal amplitude collected wirelessly is high, and the waveform is a standard sine wave, when the frequency rises above 1 kHz and the accuracy of the acquisition amplitude is reduced; this is related to the sampling frequency set to 4 kHz. When the peak-to-peak amplitude of the input signal decreases, the signal amplitude at the receiving end is basically correct; however, the quality of the waveform has declined, and there is distortion in the waveform. Since wirelessly collected signals are more susceptible to interference from outside sources, a three-point smoothing filter is applied based on the wireless original signal.

In order to further test the performance of the wireless module, the designed wireless vibration sensor, applied in the online monitoring of a 110 kV three-phase power transformer in operation in Fuyang Substation of Hangzhou Electric Power Bureau, the wired and wireless sensor modes are used to monitor and compare the waveforms. The wired sensor used in the test is an ICP sensor, and its sensitivity is 500 mV/g.

The measuring points of the wired ICP sensor and the wireless sensor are very close, in order to minimize the difference introduced by the two types of sensors due to different placement positions. Comparison of the waveforms of the wired and wireless collected signals at the measuring point No. 1 is shown in Fig. 6. Comparison of the frequency spectrum of the wired and wireless collected signals at the No. 1 measuring point is shown in Fig. 7.

In the waveform graph collected by wireless sensor, it can be observed that the waveform presents a periodic law, and from the spectrogram, it can be observed that the energy is concentrated and scattered on the octave of 50 Hz, and it conforms to the vibration law of the transformer. Also, it can be seen from the waveform comparison chart and spectrum comparison chart of the wired and wireless acquisition of the above No. 1 measuring point that the shape and amplitude of the waveform obtained by wireless acquisition and wired acquisition and the distribution of the frequency spectrum are basically the same. Signals collected wirelessly are more susceptible to external signals; therefore, a three-point smoothing filter is performed based on the received wireless original signal. The

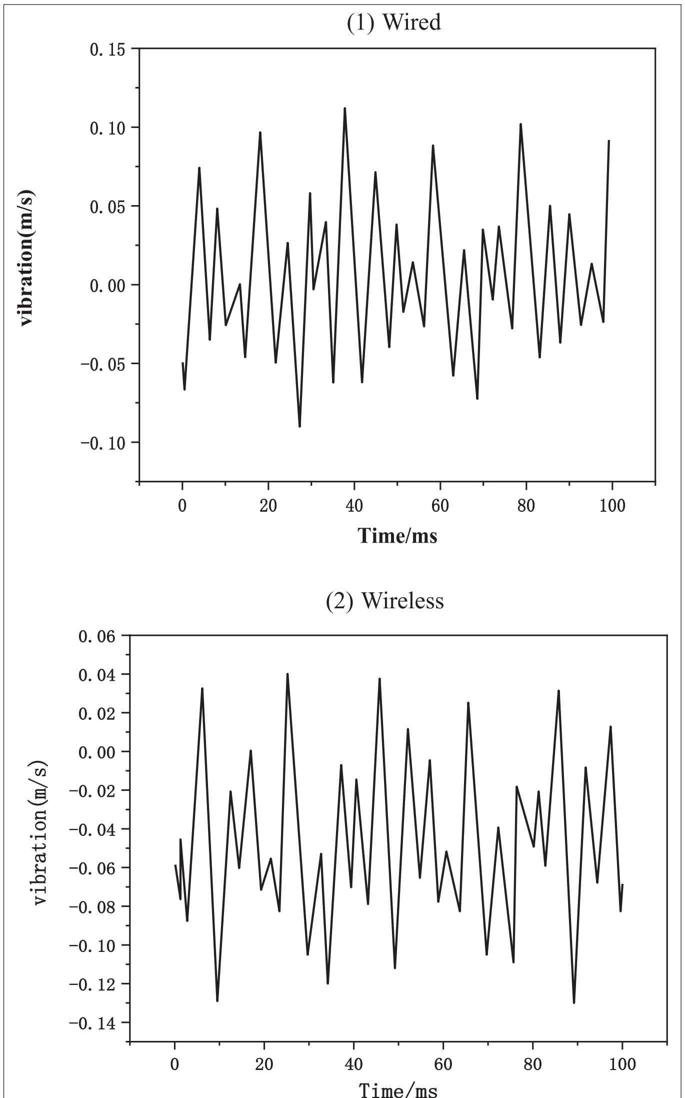

Fig. 6. Comparison of acquisition waveforms of No. 1 measuring point sensor.

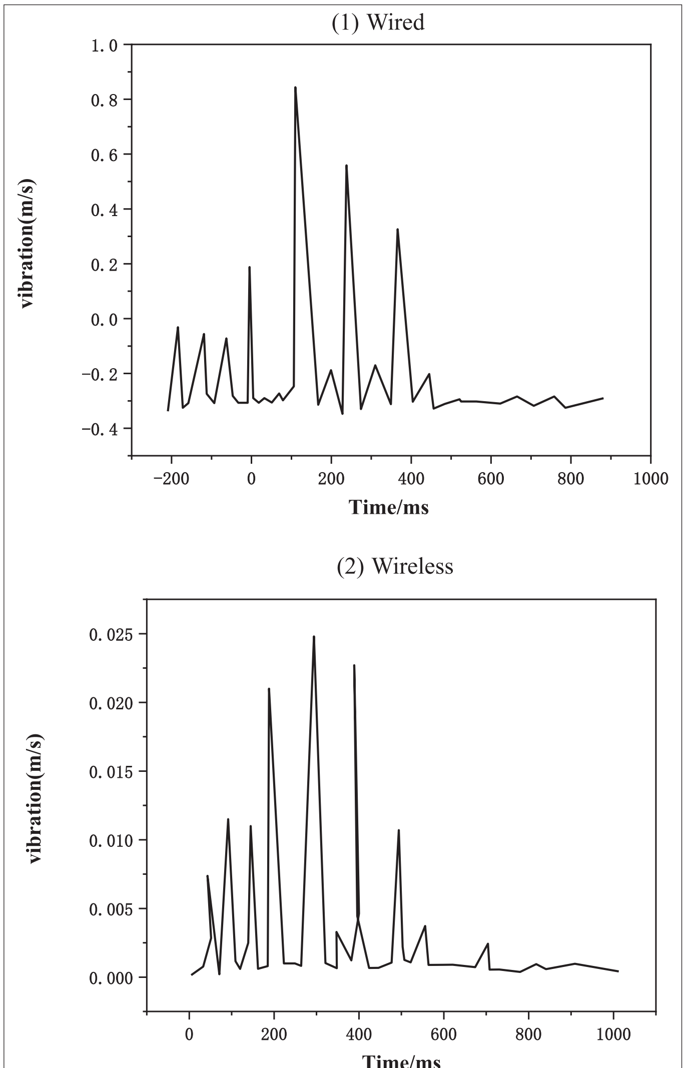

Fig. 7. Comparison of the spectrum collected by the No. 1 measuring point sensor.

signal amplitude at the receiving end is essentially right as the peak-to-peak amplitude of the input signal declines, but the waveform quality has decreased and there is distortion in the waveform. The filtering result is compared with the wired acquisition result, and the consistency of the signal is found to be stronger, which is particularly obvious in the waveform graph. In summary, the analysis of the indication composed by the wireless device and the comparison of signals obtained by the wireless collection method and the wired collection method show that the wireless sensor can collect the vibration signal of the transformer tank wall, and it has performance indicators comparable to wired ICP sensors.

V. CONCLUSION

For the vibration state monitoring of mechanical equipment based on wireless sensor network technology, a transformer vibration wireless sensor module based on CC2530 and ADIS16006 was designed. It is primarily concerned with the software and hardware design of ZigBee network node terminals and coordinators. The network is designed with low cost and low power consumption as the design goal; it reduces the inconvenience of on-site wiring and the errors that may be introduced in the wired sensing scheme. The results of shaking table test and field test show that the sensor module can basically meet the accuracy requirements of transformer vibration monitoring. Furthermore, the wireless sensor network in this architecture has the following inherent issues: for instance, there are certain requirements for on-site environmental disruption, the communication range is limited, the transmission rate is low, etc. As a result, the system is only useful in circumstances where real-time data requirements are minimal, communication distances are limited, and 2.4G is available.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – Y.P., Y.W., V.J.; Design – Y.P., R.R., V.J., K.K.B., R.K.; Supervision – Y.W., V.J.; Funding – ; Materials – Y.P., K.K.B., N.K.; Data Collection and/or Processing – Y.P., N.K. K.K.B.; Analysis and/or Interpretation – Y.P., Y.W., V.J., R.K., N.K.; Literature Review – Y.P., Y.W., R.R., R.K., N.K.; Writing – Y.P., R.R. K.K.B.; Critical Review – Y.W., V.J., N.K.

Declaration of Interests: The authors declare that they have no competing interest.

Funding: The authors declared that this study has received no financial support.

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Yuhua Peng was born in Wuhan, HuBei, P.R. China. She received her Master's degree from Wuhan University, P.R. China. Now, she works in Artificial Intelligence School, Wuchang University of Technology. Her research interests include Artificial intelligence and Computer application.

Ying Wang was born in Wuhan, HuBei, P.R. China. She received her doctorate degree from Huazhong University of Science and Technology, P.R. China. Now, she works in School of Mechanical Engineering, Wuhan Polytechnic University. Her research interest includes computational intelligence and Automatic control engineering.

R. Raffik is working as an Assistant Professor in the Department of Mechatronics Engineering at Kumaraguru College of Technology. He completed his Bachelor's & Masters in Mechatronics Engineering at Kongu Engineering College. He is pursuing his research in Robotics. His areas of interest are Robotics, Industrial Automation, Mechatronics, Hydraulics & Pneumatics, and Unmanned Aerial Vehicles

Dr. Vishal Jagota received his Bachelor of Engineering in Mechanical Engineering from Maharishi Dayanand University, Rohtak, India. He received his M. Tech. in Mechanical Engineering & Machine Design from the Punjab Technical University, Jalandhar, India. He received his Ph.D. in Mechanical Engineering from the National Institute of Technology, Hamirpur, HP, India. He worked in industry for two years and has been teaching for the past 11 years at various prestigious Technical Institutions. Currently employed at Madanpalle Institute of Technology & Science in Andhra Pradesh, India, in the Department of Mechanical Engineering. His research interests include Material Characterization, Tribology, Steel Heat Treatment, Statistical Analysis, and Simulation. He has published more than 30 research articles in a number of reputed National and International journals and conferences that are indexed in SCOPUS, ESCI, and SCI.

Komal Kumar Bhatia is working as Professor in the Department of Computer Engineering at J. C. Bose University of Science and Technology and has a work experience of 20 years. He received his B.E., M.Tech., and Ph.D. degrees in Computer Engineering in 2001, 2004, and 2009 respectively. He has guided eight Ph.Ds. and guided seven Ph.D. scholars. He has also guided more than 100 M.Tech. dissertations. He has published more than 100 research papers in reputed journals and conferences and his areas of interests are Information Retrieval Systems, Hidden Web, and Web Mining. Currently, he is also working as Dean in the Faculty of Informatics & Computing and Chairman of Department of Computer Engineering. He is also a member of several Professional bodies at National/International level.

Dr. Ravi Kumar is currently working as Associate Professor at Jaypee University of Engineering and Technology, Guna, with an experience of more than 18 years. He joined Jaypee University of Engineering and Technology in year 2005 as lecturer and completed Ph.D. from the same University in year 2013. Before Ph.D., he completed his B.E. and M.Tech in Electronics and Communication Engineering with specialization in Microwave Engineering. He also has 1 year administrative experience in Pentasoft Technologies Pvt. Ltd as Center Manager. He is member of various professional bodies such as senior member of IEEE, Fellow member of IETE, senior member of UACEE, and many more. He has published 26 research papers in referred Journals (including SCI and Scopus indexed journals), 16 conference papers at International & National level, 11 National & International level patents, and authored 3 Books in Electronics and Computer Science domain. He is also a editorial board member of many international journals and reviewer of various IEEE, Springer, Elsevier, Wiley, and other international publisher's journals. He received IEEE Best Paper award in 2012 and currently co-opted as Executive Committee member of IETE, MP subsection. His research interest includes Advanced Communication Systems using AI and ML, Advanced Antenna Design, Biomedical Signal and Image Processing.

Nithiyananthan Kannan is currently working as Professor in the Department of Electrical Engineering, Faculty of Engineering, King Adbulaziz University, Rabigh branch, KSA. He has 22 years of Teaching/Research experience. He completed his Ph.D. in the area of Power system engineering at College of Engineering Guindy campus, Anna University, India, in the year 2004. He had published books in the area of Electrical and Electrical Engineering. His area of interest is Computer Applications to online Power System Analysis, Modelling of Power Systems. He could able to publish more than 80 research papers in reputed International Journals.