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Original Citation

Feng, G., Mustafa, A., Gu, J.X., Zhen, Dong, Gu, Fengshou and Ball, Andrew (2013) The Real-time Implementation of Envelope Analysis for Bearing Fault Diagnosis based on Wireless Sensor Network. In: Proceedings of the 19th International Conference on Automation and Computing (ICAC) 2013: Future Energy and Automation. ICAC 2013 . Brunel University, London, UK. ISBN 978-1908549082

Proceedings of the 19th International Conference on Automation & Computing, Brunel University, London, UK, 13-14 September 2013

The Real-time Implementation of Envelope Analysis for Bearing Fault Diagnosis based on Wireless Sensor Network

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Abstract--Wireless sensor network (WSN) is gaining popularity in condition monitoring (CM) fields. However, enormous datasets obtained by data acquisition systems with high sampling rate cannot be transmitted effectively via a WSN due to its limited transmission speed. This may lead to the loss of significant information for condition monitoring and fault diagnosis, hence affecting the accuracy of diagnostic results. Local processing can be employed to improve the transmission efficiency; in that the acquired data is processed to extract the features locally for data compaction, and then only the analysis result is sent through the WSN. Therefore, the transmission load is reduced significantly and all the useful information is guaranteed to be transmitted for examining accurate detection results. However, the commercially available wireless sensors are usually not competent enough to fulfill complicated signal processing algorithms. In this paper, an intelligent WSN node capable of signal processing is proposed to improve the transmission efficiency of the WSN system and the envelope analysis algorithm is implemented on the sensor for bearing fault diagnostics. A bearing test rig is set up to verify the performance of this design. According to the test results, if a band-pass filter with 1000 Hz bandwidth is applied in the envelope analysis process, the data to be transmitted could be reduced by nearly 95%, which will make the real-time transmission effectively.

Keywords-Wireless Sensor Network (WSN); Envelope Analysis; Fault diagnostic; Local Processing

I. INTRODUCTION

In most applications, the condition monitoring (CM) system is carried out through wired communications for measuring signals, such as measuring vibration, temperature, chemical and acoustics etc. This usually requires expensive communication cables to be installed for ensuring the transmission quality of the measured signals. This restricts their applications in industrial plants because of their high cost. Recently, Wireless sensor network (WSN) is being widely applied in CM systems for data transmission, because of its inherent advantages, such as low cost, low latency, self-organization and high reliability. Various measured signals, such as temperature, voltage and current have been transmitted using WSN [1][2]. Various standards have been adopted for the wireless data transmission. Zigbee is a standard used widely in the wireless sensor networks (WSN) with a maximum transmission speed of around 250 kilobits per second (kbps). Generally, the signals acquired with high sampling rate will produce a large dataset, and the entire raw data cannot be transmitted effectively by Zigbee due to its limited transmission speed, especially for real-time applications [3]. For example, if a measured signal is sampled at a rate of 10 kHz with 16-bit resolution, the raw data for one second will reach 160 kb. If more channels or more wireless nodes are added, the network will be overburdened; some of the required data packets will be dropped due to congestion.

Vibration is an effective condition monitoring technique that has been used extensively in the CM field [4]. However, its application has been limited in a WSN because of its relatively high sampling rate. Recently, the idea of on-sensor or local processing has been proposed to solve this problem. Instead of directly forwarding the raw data to the sink node, the acquired data are processed on the sensor node in advance, only the analyzed results will be sent through the wireless network, thus, transmission load would be significantly reduced and the sent data will contain all the useful information for further analysis [5][6].

L. Hou and N. W. Bergmann performed fast Fourier transform (FFT) of 512 points on the vibration signal and extracted 12 most frequently occurring frequency components in the frequency domain as the fault feature for data transmission in a wireless system [5]. After some data fusion methods added, the payload transmission data was reduced from 1024 bytes to 8 bytes, which is a high compression rate with a data reduction of more than 99%. However, the sampling rate for the vibration signal was only 3.1 kHz, which is too low for some applications..

Based on the consideration of power consumption and large scale deployments, wireless sensors are usually designed to be compact with low cost. Therefore, the memories are limited and computational capabilities are restricted [6]. For example, the typical wireless sensor development platform Xbee Pro ®ZB, has only 2 kilo bytes (KB) RAM and a 8-bit processor running at 50.33MHz [7]. The system-on-chip (SOC) solution CC2530 has 8 KB RAM on chip and a 8-bit processor running at 32MHz [8]. These WSN nodes are not competent enough to implement complicated signal processing methods as complicated as FFT in real-time. In this paper, an improved intelligent WSN node is designed for rolling bearing fault diagnostic. It has the capability of compressing the data effectively through fulfilling complicated signal processing algorithms locally.

The envelope analysis was employed for extracting the fault features of the monitored rolling bearing. Envelope analysis is a classical diagnosis algorithm that is widely used for early detection of faults in gearboxes and rolling element bearings [9][10]. In this application, the sampling rate is set at 10 kHz and 2048 points are used to process FFT calculation. Since the interested frequencies lie within a 500 Hz range within the envelope analysis results, only 103 points of data needs to be transmitted, therefore, the transmission data is reduced by 95%, which greatly decreases the load of the WSN and allows real time transmission. Furthermore, if the results of envelope analysis are averaged by four times or more, the data for transmission can be further reduced. In order to prove the performance of the proposed design, a bearing test rig was set up. The test results show that the proposed algorithm is an efficient method for use in a WSN system for fault diagnosis of a rolling bearing.

II. SYSTEM IMPLEMENTATION

This study mainly focuses on the implementation of the feature extraction algorithms on the WSN node in real-time for a rolling bearing fault diagnostic. In this section, the system will be introduced in three parts: firstly the WSN node structure which is high performance and able to implement complicated calculations, then the envelope analysis which is the algorithm adopted to extract the feature of the vibration signal and finally local signal processing techniques adopted to ensure the real-time implementation of the algorithm.

A. WSN node structure

A WSN system usually composes of a sink node and several WSN nodes. In a WSN system, a node collects and transmits data wirelessly to the sink node, and then the sink node sends data received from different nodes to the data processing center for further analysis via USB, Ethernet, etc. As it shows, the WSN node is a key component of the system. The main structure of the WSN node in this design is shown in Fig. 1, which consists of piezoelectric (PE) sensor, charge amplifier, core processor and the Zigbee module.

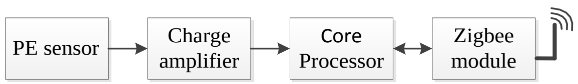


Figure 1. Main structure of the WSN node

In a node, the vibration signal is measured by the piezoelectric (PE) accelerometer, which was chosen because of its relatively low power consumption compared with the integrated electronics piezoelectric (IEPE) sensor. The IEPE sensor usually requires excitation power from a constant-current regulated or direct-current (DC) voltage source which is not always readily available, while the PE sensor does not need a power and is therefore more convenient[11].

A charge amplifier is added after the PE sensor to condition and convert the high impedance output of the PE sensor to a low impedance signal, which will allow it to be effectively collected by the analog to digital converter (ADC). In this design, the on-chip ADC of the core processor has been used to fulfill the conversion for low power and cost considerations.

In this design, a new generation 32-bit ARM Cortex-M4F microcontroller TM4C1233H6PM is used as the core digital processor to complete the local processing. The microcontroller provides 256k bytes flash, 32kB SRAM and rich peripherals such as 1MSPS 12-bit ADCs, 8 UARTs, 4 SPIs, 4 I2Cs, USB & up to 27 timers. Most importantly, a floating point unit (FPU) is integrated inside the processor, making it especially convenient and efficient for signal processing[12]. The main function of the core processor is to compress the raw data through extracting the features of the measured signals using the designed algorithm and compact the optimal dataset for transmission by Zigbee module.

For the Zigbee network construction, the Xbee pro ®ZB module from Digi international [7] is employed to set up the Zigbee network for the data transmission. This commercial module is effective, reliable and practical for the application [13].

B. Envelope analysis

Envelope analysis is suitable for diagnostics of machinery where faults have an amplitude-modulating (AM) effect on the characteristic frequencies of the machinery [9]. In this algorithm, the power spectrum of a modulating signal is calculated and the steps of its implementation are shown in Fig. 2.

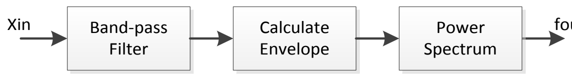


Figure 2. Procedures of envelope analysis

Firstly, a band-pass filter is applied to eliminate the low-frequency contents with high-amplitude signals due to imbalance or misalignment and high frequency noises from the measurement system, which allows a good signal-to-noise ratio to be achieved [9]. In this case, an 80-order finite impulse response (FIR) band-pass filter with the pass-band at 1000 Hz to 2000 Hz is employed to filter the vibration signal.

Secondly, the envelope of the signal is calculated, which can be fulfilled by using Hilbert transformation (HT). In this case, the measured signal can be considered as a complex signal which only has the real part [14]. Equations (1), (2) and (3) show the procedures to compute the Hilbert transformation. The real part of the analytic signal x_a for x_{in} is the original data x_{in} while the imaginary part is the Hilbert transformation of x_{in}. Then, equation (4) gives the envelope of the vibration signal.

Finally, equation (5) presents the power spectrum of the envelope. In addition, by using this method, the computing buffer can be reused, which is quite critical for a processor with limited storage.

$$X = fft(x_{in}) \tag{1}$$

$$X_a(\mathrm{n}) = \begin{cases} X(n), & n = 0, \frac{N}{2} \\ 2 * X(n), & 1 < n < \frac{N}{2} - 1 \\ 0, & \frac{N}{2} + 1 < n < N - 1 \end{cases} \quad (2)$$

$$x_a = ifft(X_h) \quad (3)$$

$$x_{env} = \sqrt{x_a .* conj(x_a)} \quad (4)$$

$$X_{env} = |fft(x_{env})| \quad (5)$$

where x_{in} is the vibration signal; X is the FFT of x_{in}; X_a is the FFT of analytic signal for x_{in}; x_a is the analytic signal for x_{in}; x_{env} is the analyzed envelope signal and X_{env} is the envelope spectrum.

C. Local signal processing techniques

To implement the signal processing algorithm in real-time based on the advances of the Cortex-M4F processor, three key techniques: double DMA buffer mechanism, full use of DSP library and CTS/RTS overflow protection have been used in programming the processor. Fig. 3 sketches the data processing modules inside the processor.

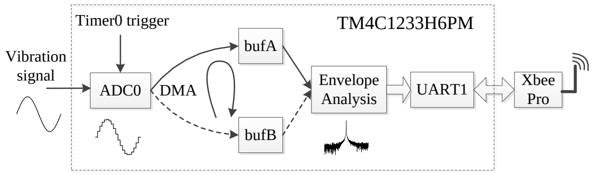


Figure 3. Data processing structure inside the processor

Firstly, a timer, with the overflow rate set at 10 kHz, is used to trigger the ADC conversion. Then, after the data conversion, Direct Memory Access (DMA) unit, a kind of coprocessor, moves the conversion results from the ADC register to the buffer bufA or bufB. Here, the DMA unit and the two buffers construct a double buffering structure, which enables the data acquisition and calculations can be accomplished in parallel, as a result, the signal processing can be implemented much efficiently [15].

Then, after the data acquisition part, envelope analysis algorithm is performed. At this stage, the Cortex Microcontroller Software Interface Standard (CMSIS) DSP library [16] is adopted to simplify and speed the development progress for the implementation of envelope analysis. Moreover, the FPU is used for high precision and efficiency considerations. For this application, the frame size is set at 2048 points and the minimum buffer for computing the envelope analysis is at least 16kB, which is half the size of the on-chip SRAM. This means 2048 points is already the maximum FFT size for this processor when using single floating-point format.

Finally, the processing results are transmitted to the Xbee pro ®ZB module via a universal asynchronous receiver/transmitter (UART) peripheral. In this application, large amounts of serial data need to be sent, thus clear to send (CTS) and request to send (RTS) flow control are employed to avoid overflowing the serial buffer on the wireless module, stopping any loss of data packets. RTS and CTS flow control can be enabled using the D6 and D7 commands on the Xbee module[17].

III. TEST FACILITIES AND FAULT SIMULATION

Fig. 4 shows a rolling bearing test rig which has been set up to determine the performance and suitability of the designed WSN node. The test rig consists of five main parts: electrical induction motor, flexible coupling, brake, bearing and shaft.

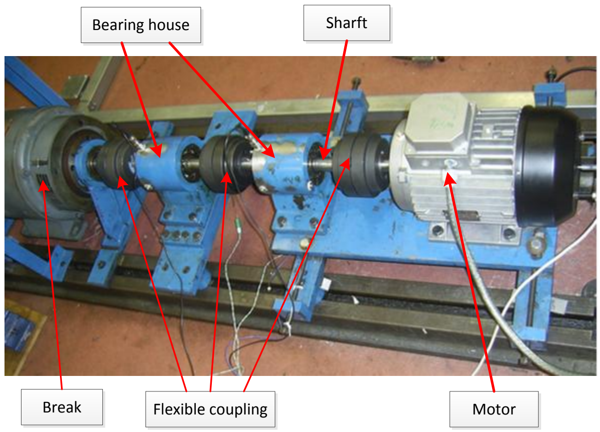


Figure 4. Test Rig Architecture

A faulty rolling bearing is simulated by scratching a marker on the outer race of the bearing. A PE sensor is mounted horizontally to the bearing housing. The model of the bearing used in the test is N406, the size of simulated fault is a maker of 0.2mm in width and 5mm in length on the outer race as illustrated shown in Fig. 5. The fault will be rolled over by rollers periodically when the bearing is running; this results in creating a fault signal modulated by a carrier signal at the resonant frequency of the bearing house [8]. The frequency of interest to detect the bearing defects is the modulating frequency.

(a) Rolling Bearing (b) Flaw on the outer race

Figure 5. Image of the rolling bearing and the simulation fault

The designed WSN node is attached to the test rig and a sink node is placed approximately 3 meters away, the sink node is connected to a personal computer (PC) through a universal serial bus (USB) to serial converter. In this test, only one WSN node is deployed for demonstration, however, more nodes can be added to the network conveniently in the future for the fault diagnosis of multiple machines. On the PC side, Matlab is adopted to read the data from the sink node and display the envelope analysis results in real time.

In the experiment, the shaft runs at a speed of 1460 revolutions per minute (RPM). The four common fault frequencies of the N406 bearing [9] are listed out in Table I. It can be seen, the maximum fault frequency is the ball pass frequency of the inner race (BPFI) at 135.5Hz, whose

3rd harmonic frequency (406.5 Hz) is within 500 Hz. Therefore, a band-pass filter with a bandwidth of 1000Hz can keep the fault frequency and its 2nd and 3rd harmonic frequencies, and remove the frequencies which are of no interest.

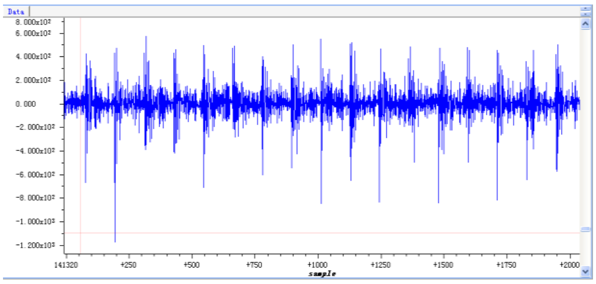
TABLE I. FAULT FREQUENCIES FOR BEARING (N406) RUNNING AT 1460 RPM

Defect location	Fault frequency (Hz)
Ball Pass Frequency of the Inner Race (BPFI)	135.5
Ball Pass Frequency of the Outer Race (BPFO)	83.5
Ball Spin Frequency (BSF)	48.4
Train or Cage Frequency (FTF)	9.3

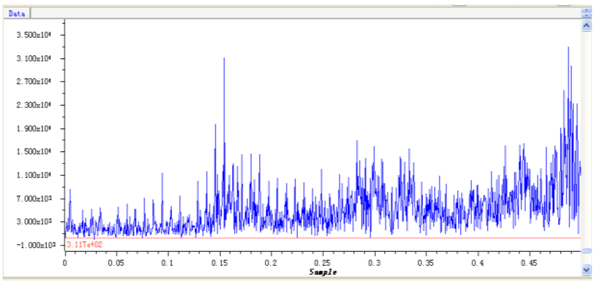
IV. RESULTS AND DISCUSSION

Code Composer Studio (CCS) is a powerful integrated development environment for developing applications for Texas Instruments embedded processors, including the processor adopted in this study. CCS is used to debug the developed program, set breakpoints at proper position and display the processing results using the graph tool. In the test, the sampling rate is set at 10 kHz and 2048 points of data are processed per frame.

Fig. 6 (a) shows the raw vibration data and some spikes appear periodically, which are caused by the fault in the outer race. The spectrum of the raw signal is shown in Fig. 6 (b). The Direct Current (DC) offset is removed from the raw signal in order to highlight the Alternating Current (AC) spectrum. It can be seen that the resonant frequency of the bearing house is at about 1500Hz. Therefore, a band-pass filter of 1 kHz-2 kHz is applied on the raw vibration signal when implementing envelope analysis.

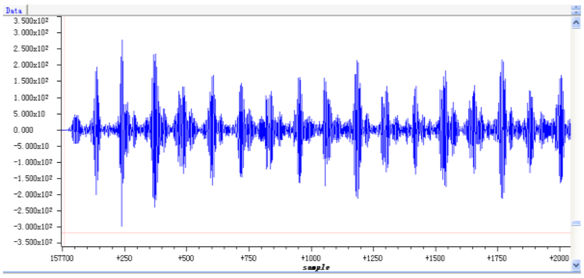


(a) Raw signal

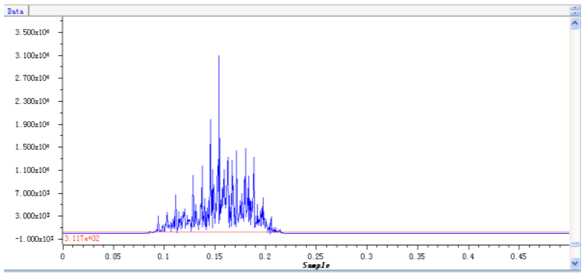


(b) Spectrum of raw signal

Figure 6. Raw signal and its spectrum



(a) Filtered signal

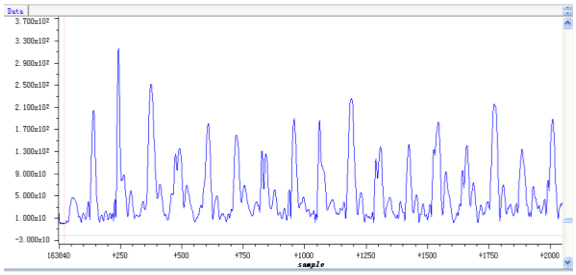


(b) Spectrum of filtered signal

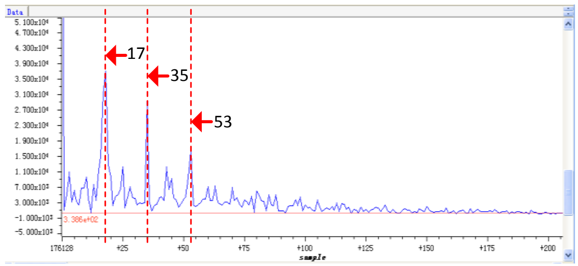
Figure 7. Filtered signal and its spectrum

The filtered signal and its spectrum are shown in Fig. 7 (a) and (b). From the figure, it can be seen that the signal has become much smoother and is limited to the band between 1000 Hz and 2000 Hz.

The analyzed envelope is shown in Fig. 8 (a), which roughly matches the outline of the filtered signal in Fig. 7(a). Fig. 8 (b) displays the spectrum of the analyzed envelope, which is partially zoomed in so as to highlight the peak frequencies. As indicated in Fig. 8 (b), the frequency spectrum peaks at 17, 35 and 53 and their corresponding frequencies are 83 Hz, 170.9 Hz and 258.8 Hz, which matches the fault frequency of the outer race and its 2nd and 3rd harmonic frequencies respectively. In other words, the outer race fault information can be detected from the results of envelope analysis.



(a) Envelope



(b) Envelope spectrum with partially zoom in

Figure 8. Envelope and its spectrum

Since all the interested frequencies in the envelope analysis results are within the 500 Hz range, the band-pass filter has limited the effective frequency to within 500 Hz, only this spectrum band data, 103 points of the envelope analysis results, are needed to be transmitted.

For a better understanding of the effects, the comparison of data amount that needs to be transmitted in different processing phases is given out in Fig. 9. Provided the data are stored with 16-bit resolution, the raw data per frame (2048 points) occupies as much as 4096 bytes, and the envelope spectrum needs to send half of that size since the spectrum is symmetric, resulting a data reduction of 50%. With the application of the band-pass filter in the envelope analysis, only 103 points of spectrum data (206 bytes) need to be transmitted, contributing a significant reduction of nearly 95%. In this case, the data output rate is reduced to approximately 8 kbps, which will reduce the transmission data in the Zigbee network and allowing real-time transmission could be achieved.

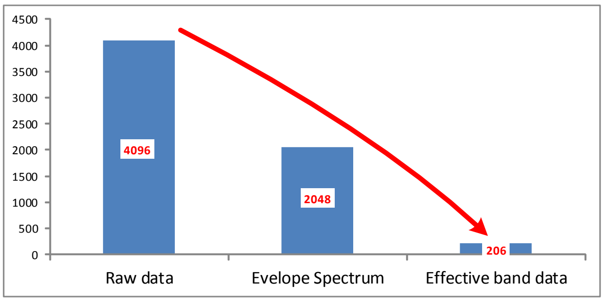


Figure 9. Comparison of the data amount

Fig. 10 gives the results of the received signal after transmission via the WSN system. It can be seen that the features for diagnosing the fault of the rolling bearing are correctly extracted and transmitted, and are the same as the corresponding band in Fig. 8 (b). Therefore, the outer race fault can be observed and detected successfully.

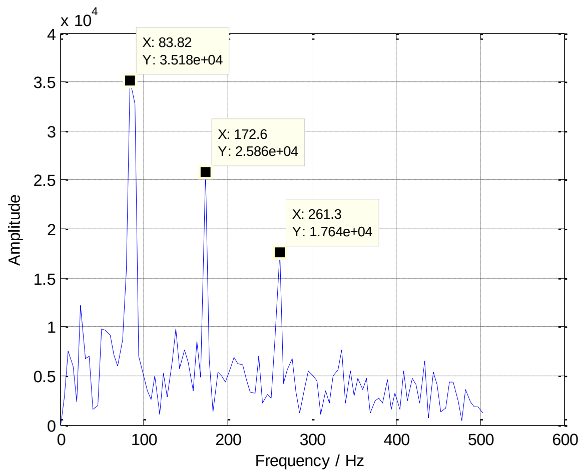


Figure 10. Matlab display result

Since the bearing's state is relatively stable in the short period when it is running, the transmitted results of neighboring frames will contain a lot of redundant data. Therefore, averaging the frequency domain can be employed to compact these redundant data and further reduce the amount of data for transmission. In addition, averaging can also bring the benefits of enhancing the signal-to-noise ratio (SNR), improving the accuracy of the detection results. If the analysis results are averaged by four times, the output rate will be reduced to 2 kbps. Fig. 11 shows the results which were averaged by four times. As it can be seen in the Fig. 11, the background noises are significantly suppressed.

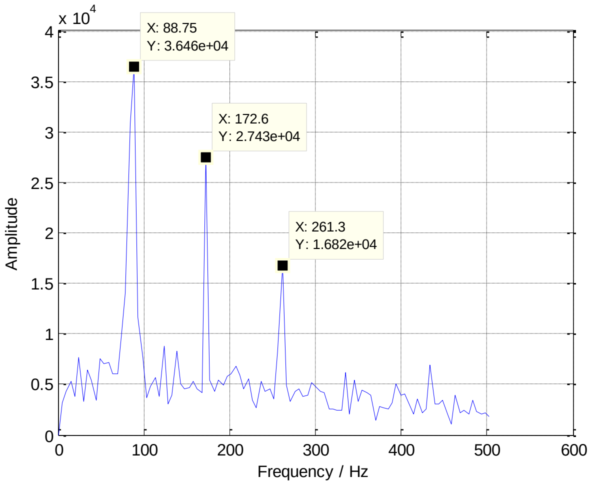


Figure 11. Averaged results by four times.

V. Conclusions

A low power and high performance WSN node is designed in this paper in order to implement fault diagnostic algorithms locally in real-time. The envelope analysis algorithm is fulfilled on the sensor and tested successfully for detecting the outer race fault features of a rolling bearing. With the application of a band-pass filter in the envelope analysis, the useful envelope spectrum band is restricted to within 500 Hz and the data amount is reduced by nearly 95%, which means that real-time transmission could be easily achieved in the WSN network. Based on the verification test, it is proved that the improved WSN system with built-in local processing algorithm is capable of compressing the dataset effectively and allowing vibration based techniques to be implemented efficiently in a WSN network for condition monitoring.

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