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A Novel Method to Improve the Resolution of Envelope Spectrum for Bearing Fault Diagnosis based on a Wireless Sensor Node

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Abstract: In this paper, an accurate envelope analysis algorithm is developed for a wireless sensor node. Since envelope signals employed in condition monitoring often have narrow frequency bandwidth, the proposed algorithm down-samples and cascades the analyzed envelope signals to construct a relatively long one. Thus, a relatively higher frequency resolution can be obtained by calculating the spectrum of the cascaded signal. In addition, a 50% overlapping scheme is applied to avoid the distortions caused by Hilbert transform based envelope calculation. The proposed method is implemented on a wireless sensor node and tested successfully for detecting an outer race fault of a rolling bearing. The results show that the frequency resolution of the envelope spectrum is improved by 8 times while the data transmission remains at a low rate.
Key words Wireless sensor network, Envelope analysis, Bearing fault diagnosis, Overlap processing, Cascading

1. Introduction

As the equipment becomes increasingly complicated, the maintenance cost of industrial machines has been growing quickly. It is estimated that approximately half of operating cost can be attributed to maintenance in most processing and manufacturing operations [1]. Currently, wired online condition monitoring (CM) systems have been successfully employed in industry, but so far have been mainly restricted to large industrial machines or laboratories due to their high cost. One major cost for these wired systems is the investment in high quality cables and their installation costs in harsh industrial environment. For cases of remote condition monitoring, the installation cost may be even higher than the cost of the sensors [2].

With the rapid development of electronics and wireless technology, wireless sensor network (WSN) is gaining increasing popularity in CM fields. It brings several inherent advantages, such as low cost, convenient installation and easy to replace and upgrade [3]. Currently, using the WSN to monitor the static signals like tem-

perature, pressure, humidity has become popular [4, 5]. However, the application of dynamic signals over the WSN is still limited, which is restricted by the conflicts between high data amount of dynamic signals and the low bandwidth of the WSN. Basically, there are two ways to monitor the dynamic signals over WSN. One way is to increase the bandwidth of the WSN, for example, employing Wi-Fi. However, it also brings new problems, such as higher power consumption in which case external power supply or frequent charging of the battery is needed. The other way is to employ on-sensor processing, in which, the raw data are firstly processed on the sensor node by the embedded algorithms and only the processing results are sent through the network. Thus, the transmission data amount can be greatly reduced. Another appealing reason for on-sensor processing is its potential to reduce power consumption of the node since the calculations on the microprocessor usually consumes less power than data transmitting [3, 6].
Bearing is widely used in the industrial plants and it is estimated that about 40% of the induction motor failures are caused by bearing failures [2] and envelope analysis has been proved as an effective method to detect the early faults on the bearing. The author realized this algorithm on a wireless sensor node and its effectiveness for reducing the data amount have also been proved through experiments [7]. This paper extends previous works and an improved method is developed to increase the frequency resolution of the envelope spectrum. It is tested successfully on the same wireless sensor node for detecting the outer race fault, which makes the implementation of envelope analysis on the wireless sensor node more meaningful.

2. Theoretical background

2.1 Envelope analysis

As a classical diagnosis algorithm, envelope analysis is widely used for the early fault detection in gearboxes and rolling element bearings, etc. [8, 9]. It is suitable for diagnostics of machinery where faults have an amplitude-modulating (AM) effect on the characteristic frequencies of the machinery [8]. Fig. 1 shows the envelope analysis to a simple modulation signal, in which, a 1500Hz carrier signal is modulated by an 80Hz sine wave. In the spectrum of the modulation signal, there are three frequency components and the 80Hz frequency component is carried to the high frequency band centered at the carrier frequency. After envelope analysis, the low frequency component is extracted out and the high frequency problem is transferred to a low frequency one. Comparatively, it is much easier to tell the modulating signal from the envelope spectrum especially when several modulating signals coexist.

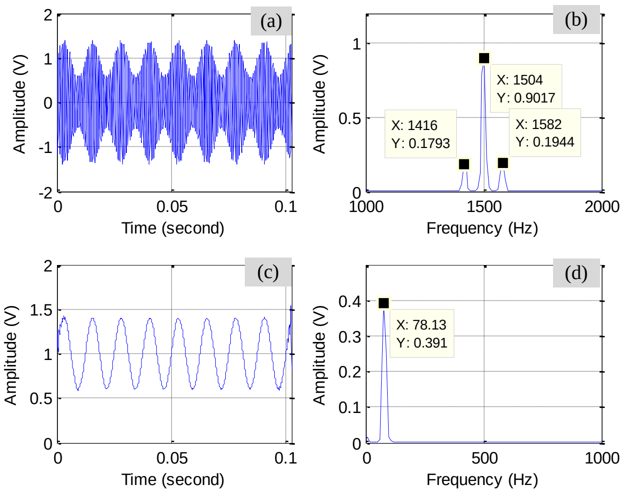

Fig. 1 Application of envelope analysis to a time waveform: (a) modulation signal, (b) spectrum of modulation signal, (c) analyzed envelope, (d) envelope spectrum

2.2. Down-sampling, cascading and overlap processing

For a signal sampled at F_S, its frequency resolution is determined by the acquisition time T, as shown in equation (1).

$$\Delta f = \frac{1}{T} = \frac{F_S}{N} \tag{1}$$

Obviously, increasing the number of samples N for calculating FFT so as to increase the acquisition time T is the only way to increase the frequency resolution. However, there is a maximum size of FFT calculations for a specific wireless sensor node. Take the processor used in [7] for example, a maximum size of 2048 points FFT calculation can be realized when using the floating point format. Since wireless sensor nodes are usually designed with limited memory size and computing capability for low power consumption and large scale deployment considerations, this means the allowable size of FFT calculation for a wireless sensor node is usually not large enough and thus the frequency resolution is not sufficiently high for obtaining accurate diagnostic results.

However, for the implementation of envelope analysis, it is possible to improve the frequency resolution of envelope spectrum by using a scheme of down-sampling and cascading the computed envelope data. This is because that the interested frequency components of the envelope signal are shifted to the low frequency band after envelope analysis. As shown in Fig. 1, after envelope analysis, the effective components are below 100Hz. For cases dealt with in [7], the interested frequency band of the envelope signal was within 500 Hz.

Meanwhile, simply cascading the down-sampled signal may bring undesirable distortions to the spectrum. As shown in the analyzed envelope in Fig. 1(c), obvious distortions appear at the front and end edge of the analyzed envelope signal. This is caused by the window effect when implementing Hilbert transform. In order to exclude these unwanted distortions, an overlap processing scheme can be employed according to [10].

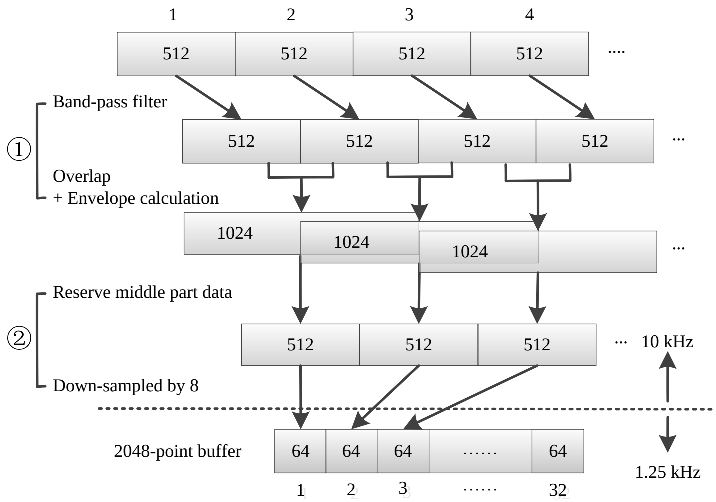

Fig. 2 Diagram for the overlap, down-sampling and cascading scheme

A processing scheme which combines the overlap processing, down-sampling and cascading is given in Fig. 2. The collected vibration data are processed frame by frame with the size of 512 points and a 50% overlap is employed in order to keep the consecutiveness of the analyzed envelope signal. As shown in the figure, the scheme consists of two main steps: envelope calculation and envelope down-sampling. In the first step, a data frame first passes through an FIR band-pass filter and then combines with last filtered data frame to form a new data frame of 1024 data points. Then the envelope of this 1024 data is computed using Hilbert transform, as descried in [7].

In the second step, only middle part of the computed envelope data is kept and down-sampled by 8 times, depending on the bandwidth of the band pass filter, to save computing memory and reduce the calculation amount. As shown in the fourth and the fifth row of the data flow diagram in Fig 2, the original 512 points of data shrink to only 64 points.

The repeat of the above two steps will allow an envelope data of 2048 points to be obtained. As the construction of the envelope data is based on the middle part of each frame, the side distortions are avoided. Moreover, because of the down-sampling operation, the envelope spectrum will have a high frequency resolution, for example, the resolution for the data described will be improved by 8 times.

3. Algorithm implementation and experimental setup

3.1 Algorithm implementation

In order to evaluate the algorithm, a wireless condition monitoring system employed is shown in Fig. 3. It consists of one sink node and one sensor node. Two Xbee wireless modules from Digi-international are employed to setup the Zigbee network. The sensor node is responsible for vibration signal collection and local processing while the sink node is used to route the processing results to the host computer for display and further analysis.

On the sensor node, vibration signal is measured using a Piezo-Electric (PE) accelerometer, which is selected because of its low power consumption compared to the Integrated Electronics Piezo-Electric (IEPE) one. A low-pass filter with 5 kHz cut-off frequency is added for anti-aliasing. Then, analog to digital conversion (ADC) and local processing algorithms are accomplished on a Cortex-M4F microcontroller TM4C1233H6PM, which has 256k bytes flash, 32kB SRAM, 12-bit ADC with 1 MSPS sampling rate and various peripherals. According to the investigation in [11], Cortex-M architecture has been chosen as the new generation core of the WSN platform for low power and high performance considerations. With the integrated digital signal processing (DSP) unit and floating point unit (FPU), Cortex-M4F core is quite efficient for implementing complicated calculations.

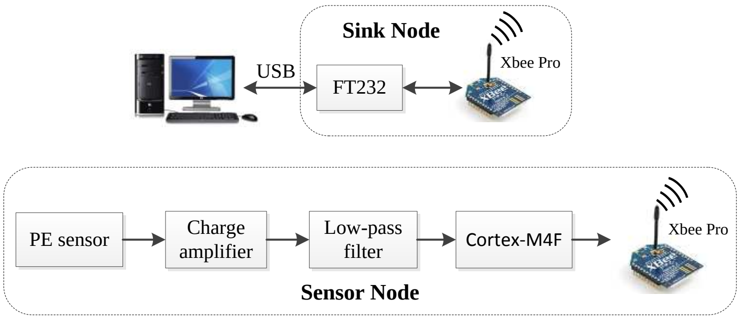

Fig. 3 Structure of sink node and sensor node

The data processing flow inside the processor is given in Fig. 4. The vibration signal is firstly sampled by the on-chip ADC, which is triggered by setting the overflow rate of a timer at 10 kHz. Then, the conversion results are moved from the ADC register to the internal buffers automatically by a Direct Memory Access (DMA) unit. When the buffers are full, an interrupt will be generated to inform the central processing unit (CPU) to process the newly collected frame data (512 points). Here, data in the frame are converted from 16-bit fixed point format to 32-

bit single floating point format for accurate calculations. Then, the overlap, down-sampling and cascading scheme described in Section 2.2 is implemented for computing the envelope spectrum. Finally, the calculated envelope spectrum is averaged by 4 times and transmitted over the Zigbee network.

As shown in Fig. 4, DMA unit together with the two buffers construct a double buffering structure, which enables the data acquisition and CPU calculations to be completed in parallel. As a result, signal processing can be implemented much efficient. The random access memory (RAM) consumed by the main buffers is as large as 24 kB, which is more than half size of the total RAM (32 kB). These buffers are used of high efficiency, especially for the main buffer *fBuf*, which is used for several calculations, such as envelope computation, down-sampling, cascading and FFT, etc.

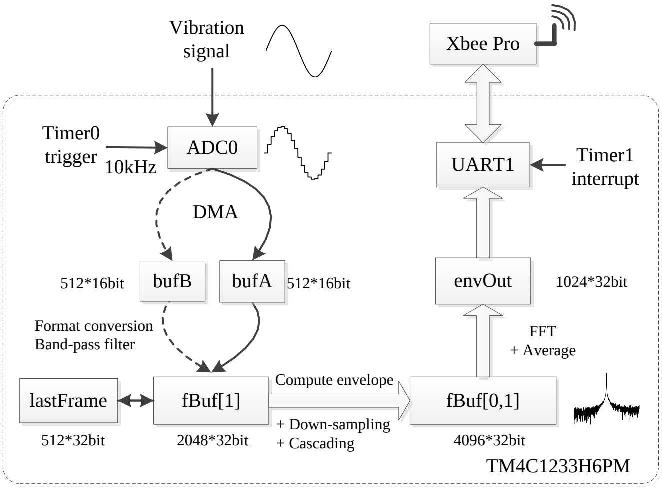

Fig. 4 Data processing flow inside the processor

3.2. Experimental setup

In order to estimate the performance of the improved algorithm, the wireless sensor node was used to detect the fault on a rolling bearing test rig shown in Fig. 5. A faulty rolling bearing with a scratch on the outer race was installed inside the bearing house. When the bearing running, the scratch will be rolled over periodically, which results in a fault signal modulating with a carrier signal at the resonant frequencies of the bearing house [8]. As explained in [7], an outer race faulty signal with the character frequency at 83.5 Hz is expected to be extracted using the envelope analysis algorithm. During the test, a PE accelerometer was mounted horizontally to the bearing house to measure the vibration signal and the sink node was placed about two meters away for receiving the processing results.

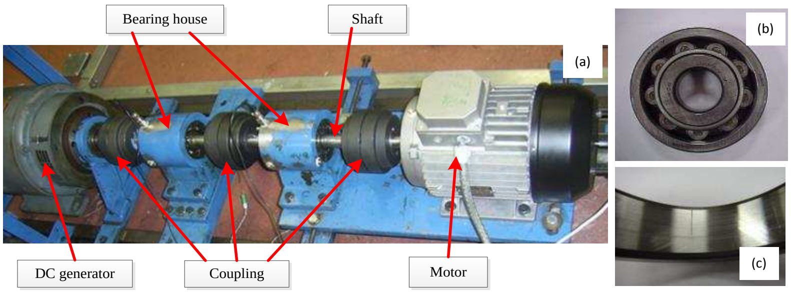

Fig. 5 Test rig: (a) bearing test rig, (b) rolling bearing, (c) defects on outer race

4. Results and discussion

4.1 Processing results on sensor node

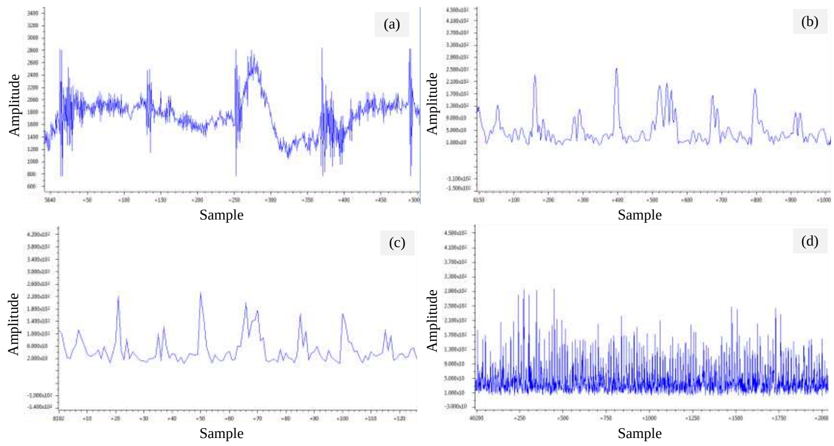

Fig. 6 Processing results on the sensor node: (a) raw data (512 points), (b) envelope (1024 points), (c) down-sampled envelope (128 points), (d) Cascaded envelope (2048 points)

The algorithm on the sensor node was developed using the Code Composer Studio (CCS) [12], which is a powerful integrated development environment provided by Texas Instrument. In order to fully examine the improved algorithm, several important internal processing results are firstly given by tracing into the program and visualizing the results via graph tools. The processing results viewed in CCS are illustrated in Fig. 6, including raw signal, calculated envelope, down-sampled envelope and cascaded envelope. As shown in Fig. 6, short period impact pulses can be noticed in the raw signal and high level noises are also observable. The high frequency components of the calculated envelope have been removed and the down-sampled envelope roughly matches calculated envelope while the points are different. As can be seen in Fig. 6 (c), the distortions at the front and end edge of the down-sampled envelope is not quite large.

The spectrum of the cascaded envelope is presented in Fig. 7. In the test, the sampling rate of the AD converter is set at 10 kHz and after 8 times' down-sampling, the true sampling rate of the cascaded envelope is 1.25 kHz. Therefore, the frequency resolution after 2048 points' FFT calculation is about 0.61 Hz. The index and corresponding frequency are illustrated in Fig. 7. As it shows, as high as the fourth harmonic of the outer race fault frequency can be clearly observed. This has indicated the existence of the outer race fault on the rolling bearing.

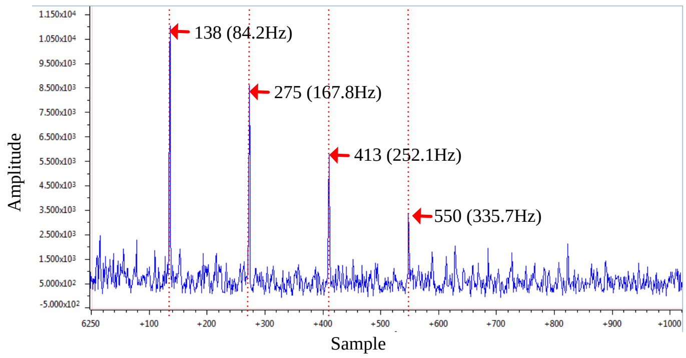

Fig. 7 Spectrum of the cascaded envelope

4.2 Remote results and comparison

In order to highlight the benefits of the improved algorithm, the envelope spectrum without cascading discussed in [7] is also used to analyze the signal from the same faulty bearing. The results of both methods are given in Fig. 8. Apparently, the outer race fault can be identified by both algorithms. However, the fault frequency identified from the improved algorithm is 84.23 Hz which is much closer to the expected characteristic frequency 84.5 Hz, whereas that from normal envelope algorithm is 83.01 Hz, more deviation from the expected. This shows that the improved algorithm produces more accurate and reliable diagnostic results. In addition, it can be seen that the ratio from the spectrum of the improved algorithm between the amplitude at the fault frequency and the background noise level is more than 6 while that from the normal envelope spectrum is less than 5. This means that the improved algorithm provides a higher signal to noise ratio (SNR) for better detection and diagnosis performance.

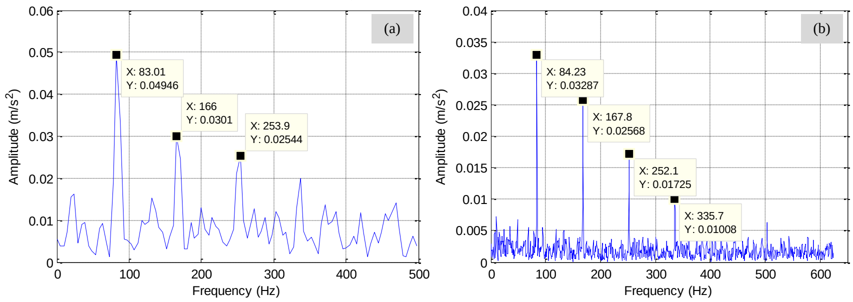

Fig. 8 (a) Envelope spectrum without cascading (2048 points) (b) Envelope spectrum with cascading and overlap processing

The improved method not only increases the resolution but also performs well in the data amount reduction. Table 1 summarizes the effective data rate per second for different processing stages on the sensor node. All the data are supposed to be stored with 16-bit resolution. As it shows, the improved algorithm just transmits a bit more data than the envelope spectrum without cascading. If only data within 500Hz are transmitted in the improved method, the data rate is even slightly lower. If frequency averaging is added, the transmitting rate can be further reduced.

Table 1 Effective data rate comparison

Data type	Data rate (kbps)
Raw data	160
FFT of raw data	80
Envelope analysis without cascading	8
Envelope analysis with cascading	9.7
Envelope analysis with cascading (within 500Hz)	7.8

5. Conclusions

An accurate envelope analysis algorithm is developed for a wireless sensor node for bearing fault diagnosis. The key processing steps of the algorithm include down-sampling, data frame overlapping and cascading. Through these steps, the resultant envelope spectrum can be obtained on the sensor node with sufficient frequency resolution and amplitude accuracy for reliable diagnostic results. Experimental evaluation shows that after down-sampling and cascading, the frequency resolution was increased by 8 times, compared with normal envelope algorithm, and the side distortions caused by Hilbert transform is avoided by a 50% overlapping scheme. With these improvements, the tested bearing fault can be identified reliably in the envelope spectrum.

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