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Efficient implementation of envelope analysis on resources limited wireless sensor nodes for accurate bearing fault diagnosis

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ABSTRACT

With the fast development of electronics and wireless communication technologies in recent years, intelligent wireless sensor nodes are becoming increasingly popular in the online machinery condition monitoring systems. They bring a number of benefits, such as reduced investment on the installation and maintenance of expensive communication cables, ease of deployment and upgrading. For the condition monitoring of dynamic signals, distributed computation on wireless sensor nodes is getting popular with wireless sensor nodes becoming more computation powerful and power efficient. As a widely recognised algorithm for bearing fault diagnosis, envelope analysis has been previously proved suitable for being embedded on the wireless sensor nodes to effectively extract fault features from common machinery components such as bearings and gears. As a continuation, this paper studies into several envelope detection methods, including Hilbert transform, spectral correlation, band-pass squared rectifier and short-time RMS. Regarding to the fact that only low frequency components in the bearing envelope is of interest, spectral correlation can be simplified for fast calculation and short-time RMS method can be considered as a simplified band-pass squared rectifier, in which partial aliasing is allowed. Thereafter, spectral correlation and short-time RMS are employed to speed up the calculation of envelope analysis on a wireless sensor node, which thereafter provides the potential to reduce power consumption of wireless sensor nodes. The computation speed comparison shows that the spectral correlation method and short-time RMS can speed up the computation speed by more than two times and five times in comparison with the Hilbert transform method. The simulation study shows that spectral correlation and short-time RMS based methods achieves similar level of accuracy as Hilbert transform. Furthermore, the experimental study shows that spectral correlation and short-time RMS based methods can well reveal the simulated three types of bearing faults while with the computation speed significantly improved.

1. Introduction

With the fast development of electronics and wireless communication technologies in recent years, intelligent wireless sensor nodes are becoming increasingly popular in the online condition monitoring (CM) systems [1,2]. They bring numerous benefits, such as reduced costs of the installation and maintenance of expensive communication cables, ease of deployment and upgrading.

In a vast number of scenarios, wireless sensor nodes are powered by batteries, which means they have limited energy and need to be changed/replaced regularly. To reduce such maintenance operations, wireless sensor nodes are usually designed with restricted computation capability and limited memory to keep their power consumption to a minimum level and thus prolong their lifespan. In recent years, different energy harvesting techniques are emerging to provide power for the sensor nodes by absorbing energy from their ambient environment, like wasted heat [3] or mechanical vibrations [4] from machines. By utilising such energy resources, it is expected to significantly prolong the lifespan of these wireless sensor nodes. In the meantime, energy harvested from such resources are usually limited, for example, the energy harvested from temperature gradient is only 10 μW/cm^3 and that from vibrations is about 200 μW/cm^3 (for consultancy, the energy from direct sun is 15,000 μW/cm^3) [5]. Therefore, it is still crucial to utilise the limited power wisely.

To minimise power consumption, the popular wireless communication protocols utilised in the wireless sensor networks typically have a low transmission data rate. For instance, the

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maximum data rate of Zigbee and WirelesHart is 250 kbps and that of Bluetooth Low Energy (BLE) is restricted to 1 Mbps. In practice, their data throughput can be even lower than this due to packet overhead, multi-hop and transmission faults [6]. Such a data throughput is sufficient for static type signals, like temperature, pressure, etc. However, they become incompetent for dynamic type signals, like vibration, acoustics and motor current. In practice, these dynamic signals are widely employed for the condition monitoring of rotating machines and are usually more helpful for analysing dynamic behaviour and diagnosing faults in such machines [7].

For processing such dynamic signals, distributed computation scheme can be more suitable than the common centralised computation scheme. In distributed computation scheme, the large raw data set is pre-processed on the wireless sensor nodes and only the resultant data set containing sufficient diagnosis information is transmitted over the bandwidth limited wireless network. By utilising such a scheme, not only the limited bandwidth can be well utilised but also it has the potential to save the valuable power energies of sensor nodes [8].

With the advancement in electronics technology, the sensor nodes are becoming more powerful, with more computation capability but less power consumption. This has reduced the challenges in embedding intelligent signal processing algorithms on resource limited wireless sensor nodes. For this reason, distributed computation is becoming increasingly popular in wireless CM in recent years. In [9], Sreenuch et al. proposed an approach for distributed CM systems that offers a reusable software architecture for a number of applications. Yin and Zhong [10] monitored rotating auxiliaries at power plants based on a distributed wireless vibration based CM system, in which they employ a data-level fusion for comparing the similarity of adjacent data and a task-level fusion for providing the strategy of sending data and the way to judge nodes' survival. Hou et al. [1] proposed a scheme for induction motor condition monitoring and fault diagnosis based on motor stator current and the vibrational signatures. In this system, feature extraction and classification by the neural network classifier are implemented on the node and decision level fusion is executed at the centre.

As a widely accepted algorithm for the fault diagnosis of bearings and gears, envelope analysis has been proved to be an effective method for extracting bearing fault features on resources limited wireless sensor nodes. The authors implemented envelope analysis on a wireless sensor node to extract bearing fault features and the results showed that envelope analysis can produce a small resultant data set while retaining key bearing fault diagnosis information [11]. On this basis, a down-sampling and cascading scheme was proposed to increase the envelope spectrum resolution so as to improve the fault diagnosis accuracy [12]. Furthermore, the fast kurtogram method was brought into the wireless CM network to adjust the band-pass filter adaptively [13], which has improved the robustness of the envelope analysis. Although the previous implementations have been optimised to well utilise the limited computation and memory resources, the calculation of envelope analysis, especially the envelope detection part, is still rather time consuming, requiring the embedded processor to run almost at full speed to finish the frame calculations in time.

This paper studies into the envelope analysis and tries to find more efficient implementations suitable for resources limited wireless sensor nodes. The structure of this paper is organised as follows. Section 2 discusses the theoretical background for the envelope detection methods, including envelope analysis, spectral correlation, band-pass squared rectifier and short-time RMS. Then, spectral correlation and short-time RMS are selected for implementation in Section 3. A simulation study is conducted in Section 4 to prove the effectiveness of the implemented methods for extracting bearing fault features and an experimental study is performed in Section 5 to compare the processing results of Hilbert transform, spectral correlation and short-time RMS. Finally, the conclusion is drawn in Section 6.

2. Theoretical background

2.1. Envelope analysis and its implementation

Envelope analysis calculates the frequency spectrum of the envelope of a signal. It is suitable for extracting fault features from impulsive and modulating type signals, which can be found in many key machinery components, such as bearings [14,15], gears [16], turbines [17] and valves [18]. This type of signal is characterised by the presence of a periodic repetition of sharp peaks modulated by high-frequency resonance components [19]. Especially for rolling bearing diagnostics, envelope analysis has been recognised as the benchmark method over many years of development [20,21].

As presented in Fig. 1, the envelope analysis mainly includes three steps: band-pass filtration, envelope detection and power spectrum calculation. The band-pass filter is employed to enhance the signal to noise ratio (SNR) by rejecting low-frequency high-amplitude signals caused by imbalance or misalignment and eliminating random noises outside the pass-band [15]. The envelope detection extracts the modulating fault signal and transfers the high-frequency problem to a low-frequency one. The power spectrum step shows the frequency components in the detected envelope, namely envelope spectrum. By observing the envelope spectrum, the existence of localised bearing faults can be easily verified.

From the previous implementations, it is found the envelope detection is the most time consuming part in the calculation of envelope analysis. Normally, envelope analysis is performed by the Hilbert transform (HT) based method due to that it is more precise and is not sensitive to the carrier [22]. Supposing the HT of a real valued modulating signal $x(t)$ is $\tilde{x}(t)$, they can compose a complex signal $x_a(t)$ as presented in (1), such a signal is usually named as analytic or quadrature signal [22].

$$x_a(t) = x(t) + j\tilde{x}(t) \tag{1}$$

By calculating the amplitude of an analytic signal, the envelope of $x(t)$ can be obtained. The Fourier transform of the analytic signal $x_a(t)$ can be expressed as:

$$X_a(f) = \begin{cases} 2X(f), & f > 0, \\ X(f), & f = 0, \\ 0, & f < 0 \end{cases} \\ = 2u(f)X(f) \tag{2}$$

where $X(f)$ is the Fourier transform of $x(t)$ and $u(f)$ is the step function.

A straight forward implementation of HT is the frequency domain method, as presented in Fig. 2. In this method, an HT window is forced to apply on the spectrum $X(f)$ to obtain $X_a(f)$, which is then used to calculate the analytic signal $x_a(t)$. It can be observed this implementation includes two forward fast Fourier transform (FFT) and one inverse FFT (IFFT), which are the most time consuming part. This is the approach that the authors have employed in

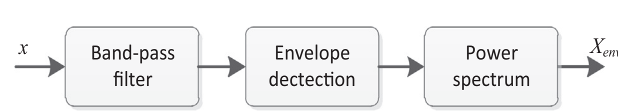

Fig. 1. Procedures of envelope analysis.