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Condition monitoring and fault diagnosis of motor bearings using undersampled vibration signals from a wireless sensor network

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A B S T R A C T

Wireless sensor networks (WSNs) which consist of miscellaneous sensors are used frequently in monitoring vital equipment. Benefiting from the development of data mining technologies, the massive data generated by sensors facilitate condition monitoring and fault diagnosis. However, too much data increase storage space, energy consumption, and computing resource, which can be considered fatal weaknesses for a WSN with limited resources. This study investigates a new method for motor bearings condition monitoring and fault diagnosis using the undersampled vibration signals acquired from a WSN. The proposed method, which is a fusion of the kurtogram, analog domain bandpass filtering, bandpass sampling, and demodulated resonance technique, can reduce the sampled data length while retaining the monitoring and diagnosis performance. A WSN prototype was designed, and simulations and experiments were conducted to evaluate the effectiveness and efficiency of the proposed method. Experimental results indicated that the sampled data length and transmission time of the proposed method result in a decrease of over 80% in comparison with that of the traditional method. Therefore, the proposed method indicates potential applications on condition monitoring and fault diagnosis of motor bearings installed in remote areas, such as wind farms and offshore platforms.

1. Introduction

Motors and generators play important roles in the conversion of mechanical and electrical energies. Hence, they are widely used in both industrial and domestic applications. Bearings connect the motor shell/stator and motor rotor; thus, they are one of the most critical and vulnerable components in motors [1,2]. For this reason, condition monitoring and fault diagnosis of motor bearings are necessary to avoid unscheduled downtime and reduce maintenance cost [3–8].

Traditionally, sensors firstly transform the vibration, sound, motor current, and temperature signals to electrical signals. Then, a data acquisition system (DAS) acquires and quantifies these analog signals and obtains digital signals. A server collects data from the distributed DASs through cables. Finally, these data are analyzed by using specific algorithms, and then maintenance decisions can be made [9].

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Benefiting from the rapid development of semiconductors, mobile communication and cloud computing techniques, an increasing number of vital equipment and infrastructures, such as high-speed train, wind turbines, and bridges, are remotely monitored by using wireless sensor networks (WSNs) which consist of massive low-powered sensors and instrument circuits [10]. This technique is also known as Internet of Things (IoT). Without cables, IoT technology provides convenience in sensor installation, replacement, and networking.

WSN gathers large amounts of data from the monitored equipment. For instance, more than 2000 sensors are installed in a long-marshaling China Railway High-speed (CRH) train, and 10 h of operation often generate 500 GB of data (of which 500 MB are critical data) [11]. To extract useful information from the redundant *big data* for condition monitoring and fault diagnosis, many emerging artificial intelligence technologies, such as machine learning [12] and deep learning [13], have been proposed and investigated in recent years.

Apparently, big data provides sufficient information to monitor equipment from different aspects. From another aspect, too much data can cause problems, such as taking up much storage and computing resources as well as consuming higher power in signal acquisition and transmission. Specially, resources and power supply ability are always insufficient in a WSN node that runs on battery and is installed in remote areas such as a wind farm [14].

To address this issue, many signal compression techniques have been exploited in both signal transmission and signal storage. For instance, a novel signal compression method based on optimal ensemble empirical mode decomposition was proposed for bearing vibration signals [15]. A subband adaptive quantization method was introduced for compressing the mechanical vibration signals [16]. A two-dimensional lifting wavelet transform was applied to rotating mechanical vibration data compression [17]. A divide-and-compress lossless compression scheme was proposed for bearing vibration signals in WSNs [18]. Typically, these signal encoding and decoding techniques are based on some transformations or decompositions such as wavelet transform and empirical mode decomposition. However, it should be noticed that the signal should be oversampled according to the Nyquist rate before these methods can be conducted and that these compression methods require considerable computation resources.

Besides the above traditional compression techniques, a new theory called compressive sensing (CS) has attracted the attention of researchers in recent years. CS can capture and represent a compressible signal at a rate that is lower than the Nyquist rate by relying on an assumption that the signal structure is preserved in the nonadaptive linear projections [19,20]. Nevertheless, stringent requirement and complicated implementations limit the applications of CS in actual practice, and the hardware including analog-to-digital converter (ADC) and the related circuits for implementing CS has not been successfully developed until now. Hence, CS theory was just used for feature extraction from the oversampled vibration signal rather than used for signal acquisition. In other words, CS was used for post processing of the oversampled signal at present. For instance, the bearing signals were oversampled at 100 kHz and then the fault features were extracted using CS for detecting bearing faults in Ref. [20].

To sum up, the previous works mainly focused on investigating algorithms for compression and transmission of the oversampled signals. Given this, it is meaningful and interesting if the data volume can be directly reduced in the sampling procedure of ADC, which will also directly reduce the memory occupation, computation resource, power consumption and transmission time. Motivated by this, the present study proposes a method that uses undersampled vibration signal acquired from a WSN for motor bearing condition monitoring and fault diagnosis.

The rollers rolling over a localized defect within a bearing will generate a series of impulses [21–23]. The impulses excite the machine and leads to resonance. Hence, a chain of impulses can be found in the vibration waveform of a defective bearing. The bearing defective signal is a modulated signal, i.e., the impulses are modulated by machine resonance [24]. According to Nyquist theorem, the minimal sampling frequency should be higher than two-fold of the upper frequency of the resonance band. From another aspect, the bearing defective signal is a typical bandpass signal, and the original resonance band (passband) can be shifted to the baseband by exploiting a technology called bandpass sampling or undersampling, which can significantly reduce sampling rate [25].

The proposed method, which is based on the undersampling principle, consists of the following steps: 1) bearing resonance band localization; 2) analog domain bandpass filtering; 3) bandpass sampling; and 4) signal demodulation. The proposed method reduces sampling rate, data transmission time, and power consumption, while preserving the distinct signatures of the bearing defective signals. Hence, the proposed method shows potential applications for remote, continuous, and high-efficient condition monitoring and fault diagnosis of motor bearings.

The rest of the paper is organized as follows. Section 2 introduces the proposed method. Section 3 performs a simulation to illustrate the method. Section 4 introduces the experimental setup and verifies the effectiveness of the proposed method by acquiring and analyzing the bearing signals on a WSN prototype. Section 5 provides discussions and Section 6 presents the conclusions.

2. Method

2.1. Resonance band determination using kurtogram

A key step of the proposed method is shifting the passband to the baseband through signal undersampling. To achieve this goal, the resonance band of the oversampled bearing signal should be localized. In this study, the classical kurtogram method is used to select the optimal filtering band as shown below: