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A divide-and-compress lossless compression scheme for bearing vibration signals in wireless sensor networks

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ABSTRACT

Remote rotating machinery condition monitoring system based on wireless sensor networks (WSNs) is an attractive application recently. Bearing is the critical important component in rotating machinery. The bearing vibration-based condition monitoring requires huge amount of vibration data. This is a big challenge to the limited resources of WSNs. So many data compression methods are proposed, but less focus on the lossless compression. In this paper, a novel lossless compression scheme based on divide-and-compress strategy is proposed, which combines the lossy compression into the lossless compression framework to enhance the compression capability. First, the discrete cosine transform is employed in data dividing to split original data into two parts that have different data characteristics. Then, according to the characteristics, several specially designed schemes are exploited for encoding the data. As described in the experimental results, the proposed compression scheme can effectively compress bearing vibration signals without data loss.

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1. Introduction

Condition-based maintenance (CBM) is an efficient way for ensuring the safety of machinery service in industry, and the heart of CBM is the data collection of condition information through condition monitoring process [1]. Since the ease of measurement and the excellent ability to reveal machinery condition, vibration-based condition monitoring has become the most common approach [2,3]. At present, online wired condition monitoring systems have been employed in many industrial fields. However, the traditional wired monitoring systems meet challenges in some specific applications, such as the vibration monitoring of mechanical components in sealed environment or rotating environment. Furthermore, in large scale distributed condition monitoring system, cables needed for carrying sensor signals are quite expensive and difficult to install and maintain. Recently, as a potential solution to these problems, remote machinery vibration-based condition monitoring system based on wireless sensor networks (WSNs) is emerged, especially for rotating machinery [4,5], with the advantages of low cost, convenient installation, and easy relocation. In rotating machinery, bearing is the critical important element and also the most frequently and easily failed unit, the condition monitoring of bearing is of prime importance [6,7].

Wireless sensor network is the system consists of some autonomous and smart wireless sensor nodes. It gathers the interest signal (such as machine vibration signal) for monitoring the conditions of some objects. However, there are still some problems to be solved in the vibration-based condition monitoring system based on WSNs. For rotating machinery, in order to collect enough condition information, the monitoring system must acquire vibration signals with high sampling rates. For instance, if there are some defects in a bearing, the signals of the frequencies in range

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of 1–5 kHz will appear [8]. To reveal all kinds of problems in condition monitoring, the sampling rate must be higher than 10 kHz according to the Nyquist–Shannon sampling theorem. Therefore, in the process of bearing vibration signal acquisition, a massive amount of data generated per second that will need to be stored and transmitted to the data server. But the wireless sensor nodes always have limited storage space, computing resources and energy, and the bandwidths of communication channels among the nodes are often small. The WSNs based on IEEE 802.15.4 standard in 2.4 GHz band operate at a raw data rate of 250 kbps, but due to the impact of network protocols and data packet structures, the maximum throughput of 163 kbps can be achieved [9]. It is a tough challenge for the resource constrained WSNs to transmit the huge amount of original vibration data.

A reasonable approach to solve the data transmission issue is to reduce the data size. It can be achieved by data compression, e.g., the adaptive frequency and amplitude compression algorithm is employed in the industrial wireless data acquisition system to reduce the data redundancy [10]. Furthermore, compressing the collected raw vibration data can extend the service lifetime of the remote condition monitoring system, because the power consumption in data communication is far more than that in data computing. Several studies regarding the bearing vibration lossy data compression in remote condition monitoring system have been done. Some of those include using wavelet transform to compress vibration signals [11]; using empirical mode decomposition (EMD) to decompose and compress vibration data first, then applying differential pulse code modulation (DPCM) to further compress the signal after down-sampling [12]; adopting modified discrete cosine transform based compression scheme to compress vibration signals, and doing some improvements to make it suitable for wireless nodes [13]; using the ensemble empirical mode decomposition (EEMD) whose parameters are optimized to extract the intrinsic mode function relating to bearing fault, and this component instead of the original signal is compressed and transmitted to reduce the data transmission [14]; adopting suitable orthogonal transforms to implement sub-band decomposition, and each sub-band is compressed by a uniform adaptive quantization [15]. These bearing vibration lossy data compression methods above achieve very high compression performance, retain the essential machine defect characteristics for fault diagnosis, and perform brilliantly in some applications. However, these previous methods will result in the loss of the original data during the compression process. The high accurate data collection is one of the critical demands in some practical industrial machinery condition monitoring systems. Reserve all components of the raw data is helpful to increase the adaptability and sensitivity of condition recognition, especially in some complex condition analysis methods, such as the degradation process prediction [16,17]. It is necessary to transmit the raw bearing vibration data from the wireless sensor nodes to the data server.

To the best of the authors' knowledge, there is no effective lossless compression method for bearing vibration signal in WSNs. A similar study is the LEC compression scheme [18,19], a famous lossless data compression algorithm in WSNs. In LEC compression scheme, the differences between contiguous data are coded by a modified version of exponential-Golomb code. It achieved very good performance in temperature and relative humidity data compression. This method can be seen as a reference for bearing vibration lossless data compression, but the performance of compression is not satisfactory. There is no any kind of lossless compression method can be effectively applied to all types of data, a good data compression method must be based on its own characteristics. Bearing vibration signals are characterized with high frequency variations, so the correlations between adjacent data are significant lower compared with smooth signals like temperature and relative humidity. It is very difficult to achieve the effective lossless compression of bearing vibration data.

In this paper, a novel lossless compression scheme of bearing vibration data is presented. It is based on the inherent characteristics of bearing vibration signals and adopts a divide-and-compress strategy. In the proposed divide-and-compress lossless compression scheme, the energy concentration of discrete cosine transform (DCT) is used to divide the original bearing vibration signal into two parts that have different energy properties. Then according to the characteristics of each part, different encoding schemes is designed to effectively compress the signal. Since the compression scheme does not lose any information, it can completely restore the original signal. The main contribution of this work is to fulfill the requirement for vibration data lossless compression in WSNs, which is a relatively unexplored area to date. For this purpose, some advantages of lossy data compression is adopted into the proposed lossless data compression scheme to achieve a high compression ratio. Furthermore, this compression scheme places some special attention on its implementation in the resource constrained wireless sensor nodes.

The rest of the paper is organized as follows. Section 2 describes the proposed bearing vibration data lossless compression scheme. The experimental results of the performance of different types of bearing vibration signals are presented in Section 3. Finally, some conclusions are given in Section 4.

2. Divide-and-compress lossless compression scheme

Bearing vibration signals always consist of some high-energy periodic and harmonic signals, and some low-energy random noises. This characteristic is utilized by some bearing vibration signal lossy compression schemes. In these methods, the low-energy noise in the original signal is first filtered out or unfiltered. Then the signal is transformed into the frequency domain. The most of the energy will be concentrated on a few frequency bands in the spectrum, and quantify these high-energy components and ignore those tiny-energy components can obtain a higher compression ratio. The process of denoising or lossy quantization is the root cause of signal distortion. To avoid this loss of original information, the proposed lossless

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