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Anomaly detection in rolling element bearings via hierarchical transition matrices

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ABSTRACT

Rolling element bearings are critical components in nearly all rotating machinery. Even small physical defects can reduce the reliability and lifespan of these devices. Such defects create anomalous patterns in the bearing vibration signature. These patterns can be used to predict component failure and allow preventative maintenance. Previous work has attempted to perform anomaly detection in vibration data from rolling element bearings. This paper presents a novel approach to anomaly detection in bearing signatures using a Hierarchical Transition Matrix Model (HTMM) combined with dimensionality reduction through Symbolic Aggregate Approximation (SAX) and Discrete Wavelet Transforms (DWT). This new method is validated through both simulated and experimental data. Simulated data is generated to demonstrate strong robustness against noise and high dimensionality, and an empirical dataset (into which defects were introduced manually) demonstrates application to real-world data sources. In a ground truth meta-tagged study, our method outperforms other approaches in both speed and accuracy, automatically detecting anomalies in small spans (<0.1 s) of data with high reliability ($>99\%$) in real time.

1. Introduction

Rolling contact bearings are common in most modern rotating machinery, and are critical to the reliability of machine operation and lifespan. Bearing performance can be negatively affected by surface imperfections which cause anomalous signals to emerge as a fault progresses. These faults can ultimately lead to catastrophic system failure [1]. Early detection of anomalies can prevent such failure, reducing machine down time, repair cost, and the risk of physical injury to workers [2–4]. Monitoring vibration signals is a standard method used to infer information about bearing health state, and is a common part of many maintenance regimens [1]. Most fault detection methods developed to date are highly system specific. In this paper, an attempt is made to develop bearing-related pattern recognition and anomaly detection approaches that are applicable across a wide spectrum of systems that incorporate bearings as critical components.

An anomaly can be described as any event (or measurable signature generated from an event) that significantly deviates from what is considered normal behavior. Anomaly detection becomes more difficult in low Signal to Noise Ratio (SNR) environments and in high dimensionality data [5–8]. In this paper, a novel approach to anomaly detection in noisy signals is

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presented to isolate anomalous events in noisy, sparse, and experimental rolling element vibration data. This paper is structured as follows:

1. The data are preprocessed with a combined wavelet transform and symbolic dimensionality reduction approach to reduce the effect of noise.
2. A novel detection approach is developed using hierarchically parameterized Transition Matrices to detect anomalies in both synthetic and experimental data.
3. This approach is compared to the symbolic Nearest Neighbors search algorithm, and is shown to outperform alternative methods in both accuracy and speed.
4. Findings are summarized and future applications are proposed.

2. Previous work in fault detection in rolling element bearings

Bearings typically consist of four main components; the inner raceway, outer raceway, ball, and cage, as shown in Fig. 1. The raceways are often lubricated to decrease friction against the rolling elements, and the cage guides the balls during operation by maintaining equal spacing.

Discrete faults on any part of the bearing cause vibration change in the system, so monitoring system vibration is one method of fault detection. However, these faults can also produce other measurable phenomena: shock impulses, temperature increases, and acoustic changes, which can also be used to detect defects [9,10]. Other works have implemented image analysis of disassembled bearings to diagnose faults, which is time-consuming and requires disassembly and reassembly of the system [11].

Previous anomaly detection methods such as Bayesian filtering, artificial neural networks (ANN) and statistical methods such as Principal Component Analysis (PCA) and (Extended) Kernel Regression Analysis (KRA) have been compared against the symbolic Nearest Neighbors matching approach, which has been shown to exhibit greater capability of detection with low false alarm rates [12]. A chief disadvantage of using Nearest Neighbor searches is their computational expense. In this paper, a Hierarchical Transition Matrix Model (HTMM) is introduced to improve computational efficiency and anomaly detection reliability, and is compared to the Nearest Neighbors Euclidean norm method.

3. Background

This section details the mathematical approaches used in the development of the HTMM method including Discrete Wavelet Transforms (DWT), Symbolic Aggregate Approximation (SAX), comparison metrics such as Nearest Neighbors, and Markov Model analysis.

3.1. Discrete wavelet transform (DWT)

A common step in vibration data preprocessing is to transform signal data into the wavelet domain [13]. Performing a first level Discrete Wavelet Transform (DWT) on raw data before symbolic approximation reduces the presence of noise typically associated with high dimensionality systems [14]. Approximate and detailed wavelet coefficients are found at user-specified time shifts k to model the signal by passing the data through a high pass and low pass filter simultaneously. This is used instead of the Short Time Fourier Transform (STFT) to overcome time-frequency resolution problems [15]. The DWT can be mathematically represented by the following equation:

$$W(j,k) = \sum_{j=1}^{n}\sum_{k=1}^{n}\left[f(k)\cdot 2^{-j/2}\psi(2^{-j}n-k)\right] \quad (1)$$

where ψ is the mother wavelet function. In this work, the Daubechies (DB) family of wavelets was used for noise reduction. The DB wavelets are continuous and use overlapping windows, making their use appropriate for noise removal in

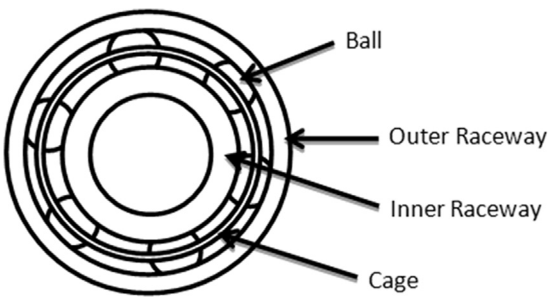

Fig. 1. Example ball bearing assembly, cross-section.