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Bearing fault detection based on hybrid ensemble detector and empirical mode decomposition

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ABSTRACT

Aiming at more efficient fault diagnosis, this research work presents an integrated anomaly detection approach for seeded bearing faults. Vibration signals from normal bearings and bearings with three different fault locations, as well as different fault sizes and loading conditions are examined. The Empirical Mode Decomposition and the Hilbert Huang transform are employed for the extraction of a compact feature set. Then, a hybrid ensemble detector is trained using data coming only from the normal bearings and it is successfully applied for the detection of any deviation from the normal condition. The results prove the potential use of the proposed scheme as a first stage of an alarm signalling system for the detection of bearing faults irrespective of their loading condition.

1. Introduction

The fault diagnosis of rolling element bearings is very important for improving mechanical system reliability and performance in rotating machinery, since bearing failures are among the most frequent causes of breakdowns in rotating machinery. For example in the case of large induction motors, bearing faults can account for up to 44% present of the total number of failures [1]. When a fault occurs in a bearing, periodic or quasi-periodic impulses appear in the time domain of the vibration signal, while the corresponding bearing characteristic frequencies (BCFs) and their harmonics emerge in the frequency domain [2]. However, in the early stage of bearing failures, the BCFs usually carry very little energy and are often suppressed/hidden by severe noise and higher-level vibrations. Consequently an effective signal processing method is of utmost importance for the extraction of damage sensitive features during the condition monitoring of bearings, especially during the initial fault occurrence.

Until now, in the field of bearing fault detection, a variety of approaches and time–frequency signal processing tools have been utilized. Wavelet transform (WT) has been widely used as a de-noising tool as well as for feature extraction. Loutas and Kostopoulos [3] presented a recent review on the applications of WT in rotating machinery diagnostics and prognostics. Abbasion et al. [4] studied the condition of an electric motor with two rolling bearings (one next to the output shaft and the other next to the fan) with one normal state and three faulty states each. De-noising via the Continuous

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Wavelet Transform (CWT) (Meyer wavelet) was conducted and Support Vector Machines (SVMs) were used for the fault classification task. Results have shown 100% accuracy in fault detection. Ocak et al. [5] developed a new scheme based on wavelet packet decomposition and Hidden Markov Models (HMMs) for the condition monitoring of bearing faults. In this scheme, vibration signals were decomposed into wavelet packets and the node energies of the 3-level decomposition tree were used as features. Based on the features extracted from normal bearing vibration signals, an HMM was trained to model the normal bearing operating condition. The probabilities of this HMM were then utilized to track the condition of the bearing.

The Empirical Mode Decomposition (EMD) introduced by Huang et al. [6] is another time–frequency tool, which has found growing applications in various fields. It is a self-adaptive method that does not depend on predefined functions as WT, Wigner Ville, Fast Fourier Transform (FFT) and short-time FFT do, and thus it is more suitable and attractive for the analysis of highly non-linear, non-stationary signals as those deriving from the vibrations of rotating machinery. EMD decomposes a signal into a number of basic constituent signals called Intrinsic Mode Functions (IMFs). Lei et al. [7] suggested a method relying on Wavelet Packets Transform (WPT) and Empirical Mode Decomposition (EMD) to pre-process vibration signals and extract fault characteristic information. Each of the raw vibration signals was decomposed with WPT using Daubechies wavelets with 10 vanishing moments "db10" at level 3. From the plethora of features extracted at each sub-band, the most relevant ones were selected via distance evaluation techniques and forwarded into a Radial Basis Function (RBF) network to automatically identify different faults (inner race, outer race, roller) in rolling element bearings.

The same research group [8], implemented a very thorough approach through an efficient damage identification scheme, which included the EMD decomposition of a vibration signal. The signal was fully decomposed into IMFs via the EMD algorithm. Then a complicated data fusion procedure via feature extraction, decrease of input vector dimensionality and, finally, pattern recognition/classification was implemented. The results effectively classified different damage conditions. However, the used number of IMFs was too large and, as a result, the whole algorithm was overly complex.

Yu et al. [9] also applied EMD on vibration signals collected from piezoelectric transducers. The experiments involved roller bearings with local faults. The bearing vibration signal was collected by a piezoelectric transducer and sampled at 4096 Hz. This frequency was adequate in order to capture the modulated pulse force of the outer bearing race fault and its first harmonic (76 and 150 Hz, respectively). The vibration signal was de-noised via WT implementation (db10 wavelet) and was fully decomposed into IMFs with the EMD algorithm. The Hilbert spectrum gave the instantaneous frequency of each IMF. Based on the Hilbert spectrum the appropriate IMFs were picked in order to evaluate the roller bearing fault evolution (outer race). The local marginal spectrum from the selected IMFs effectively identified the spectral lines of the fault. The same efficiency was observed for inner race faults also. In this case, the EMD method was proven superior to the classical envelop spectrum method for the bearing fault identification.

Peng [10] investigated the effectiveness of EMD for analyzing the non-stationary cutting force signal of machining processes. Towards the effective detection of tool breakage, the Hilbert spectrum was utilized as well as the energies of the characteristic IMFs associated with characteristic frequencies of the milling process.

Guo and Tse [11] studied the ensemble EMD (EEMD), a variation of classical EMD, which eases the problem of mode mixing, - in real vibration signals generated from defective bearings. They performed a series of investigations to reveal the relationship between the amplitude of the added white noise and the number of ensemble members for the minimization of the mode mixing problem and concluded that a higher number of ensemble members leads to smaller RMS error.

Žvokelj et al. [12,13] proposed the EEMD-based Multiscale Principal Component Analysis (EEMD-MSPCA) and the EEMD-based Multiscale Kernel PCA (EEMD-MSKPCA) techniques to overcome the non-adaptive nature of WT utilized in conventional MSPCA. They applied their techniques in vibration as well as acoustic emission recordings from large-size slow-speed bearings and highlighted the improvement of signal-to-noise-ratio and the enhanced diagnostic capability. The only potential drawback is that the proposed techniques are computationally intensive.

Most of the work involving bearing fault detection relies on information coming both from the normal as well as the faulty class. As a matter of fact among the approaches reported in the aforementioned literature only the methods proposed by Ocak et al. [5] and by Žvokelj et al. [12,13] were based solely on information coming from the normal class. However in most real life applications, data from the possible faulty modes are not readily available, making the binary (or multi-class) classification approach very difficult and impractical.

The main innovation of this article stems from the proposal of a combined and integrated anomaly detection approach to bearing fault detection. The anomaly detection is based on a hybrid or multi-strategy ensemble detector; it is the first time that an ensemble approach is applied in the bearing fault detection field. The proposed scheme is successfully applied to detect faults based on a small number of features extracted using EMD. Nowadays, EMD is a state-of-the-art signal processing method [6] that has been successfully employed in a number of fault detection studies in electrical [14] and mechanical systems [7–13]. This work shows that the suggested integrated methodology for fault detection can be envisioned as the "first line of defence" against incipient faults that can eventually build up to failures of a component or a system, with notable performance while requiring a minimum number of configuration parameters. Moreover the small number of features involved as well as the simplicity of the detectors comprising the ensemble, make this approach suitable for online implementation.

The rest of the paper is structured as follows: Section 2 summarizes the theory of EMD. The anomaly detection approach, as well as the three individual anomaly detectors employed, is presented in Section 3. In Section 4 the proposed