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A new compound faults detection method for rolling bearings based on empirical wavelet transform and chaotic oscillator

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A B S T R A C T

The rolling bearings often suffer from compound faults in practice. The concurrence of different faults increases the fault detection difficulty and the decoupling detection of compound faults is attracting considerable attentions. Recent publications report the application of the multiwavelets and empirical mode decomposition (EMD) for compound faults decoupling. However, due to limited adaptability they would induce mode mixing or/and overestimation problems in the signal processing. Particularly, the mode mixing would greatly degrade their performance on compound faults detection. To address this issue, this work presents a new method based on the empirical wavelet transform-duffing oscillator (EWTDO) for compound faults decoupling diagnosis of rolling bearings. The empirical wavelet transform (EWT) is able to extract intrinsic modes of a signal by fully adaptive wavelet basis. Hence, the mode mixing and overestimation can be resolved in decoupling processing and the compound faults can be correctly decomposed into different single faults in the form of empirical modes. Then, each single fault frequency was incorporated into a duffing oscillator to establish its corresponding fault isolator. By directly observing the chaotic motion from the Poincar mapping of the isolator outputs the single faults were identified one by one from the empirical modes. Experimental tests were carried out on a rolling bearing fault tester to examine the efficacy of the proposed EWTDO method on compound faults detection. The analysis results show attractive performance with respect to existing decoupling approaches based on the multiwavelets and EMD. In particular, our proposed method is much more reliable in decoupling the compound faults. Hence, the proposed method has practical importance in compound faults decoupling diagnosis for rolling bears.

1. Introduction

Rolling element bearings are extensively used in variant applications in industrials, such as aircrafts, marine vessels, coal mining machines, manufacturing and so forth [1]. Rolling bearings are found to be the most vulnerable components in the power transmission system [2]. A simple failure, such as a crack on the outer race of a bearing, would break down the whole transmission system and even cause severe catastrophes. Therefore, it is crucial to monitor the health state of the bearings and detect the defects in a timely manner [3–6].

The fault detection on rolling bearings has been receiving increasing interests among industry and academy in the past two decades [7]. Many researchers have discussed the vibration analysis methodologies for bearing fault diagnosis. Traditional approaches are based on the time domain or frequency domain analysis. However, due to interference of heavy background noise, it is difficult to identify

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the early defects of rolling bearings in the time or frequency spectra [8]. In order to percept and analyze the weak fault signal in rolling bearings, some state of art technologies, including the wavelet transform [9], empirical mode decomposition (EMD) [10], Teager energy spectrum [11] and order tracking [12], have been proposed for early failure detection on rolling bearings under strong noise interference. However, literature review indicates that most work investigated the single fault detection; very limited work reported the decoupling detection of compound faults for rolling bearings. Generally, a single failure in the rolling bearing would cause another fault after a certain amount rotation cycles of the bearing in practice. For instance, a spalled roller will eventually lead to cracks on inner or outer races of the bearing. Hence, in practice the rolling bearings are often subjected to compound failures that occur simultaneously. It is therefore imperative to diagnose compound faults to meet the requirement of practical applications.

Although literature reports variant fault detection technologies for rolling bearings, the diagnosis of compound faults is still a difficult task [13,14]. This is because different fault information is always coupled with each other in the time and frequency domains [13]. Previous attempts to detecting compound faults adopted intelligent classifiers, such as artificial neural network (ANN) [15], support vector machine SVM [16], or fuzzy inference [17]. It is very difficult for both researchers and engineers to understand how the intelligent classifiers work. To make the compound faults detection more readable and understandable, the decoupling technologies were developed. The wavelet transform or the EMD were used to decompose the vibration signal of compound faults into sub-signals and each sub-signal is corresponding to a single fault in the compound faults. By analyzing the sub-signals, the compound faults can be identified one by one. Yuan et al. [18] proposed the lifting multiwavelets method for compound faults detection. The vibration signal of the compound faults was decomposed into different sub-signals in different channels of the lifting multiwavelets. Then each single fault contained in the compound faults was identified by spectrum analysis on the sub-signals. Chen et al. [19] presented the redundant multiwavelets packet transform to decouple compound faults in rotating machinery. Wang et al. [20] and Xu et al. [21] employed the dual-tree complex wavelet transform to decouple compound faults of the rolling bearing into single faults. The time and frequency spectra information of each single fault was carried by its corresponding wavelet sub-band signal component. By doing so, it is able to understand the physical meaning of the compound faults detection processing. Similarly, Li et al. [22] and Wang et al. [23] adopted the ensemble EMD (EEMD) for compound faults diagnosis. The vibration signal of compound faults was decomposed into different intrinsic mode functions (IMFs) by the EEMD and each fault in the compound faults was corresponding to an IMF. By analyzing the IMF, all single faults contained in the compound faults can be detected. It should be noticed that the performance of either the wavelet transform or the EMD based compound faults detection methods is depended on the decomposition efficacy of the sub-signals. A high performance requires that the compound faults should be fully decomposed into single fault sub-signals without model mixing between the single faults [13]. However, the wavelet transform is essentially a rigid method [24], corresponding to use prescribed basis to process signals. So it cannot adaptively process a signal based on the information contained in the signal [24]. Although the EMD is a completely different approach to wavelet transform and is able to adaptively detect IMFs from a signal, it is lack of mathematical theory to guide the EMD decomposition processing, leading to model mixing or overestimation problems [24]. In order to solve this issue, the empirical wavelet transform (EWT) is proposed to construct the wavelet basis in an adaptive way [25]. Then the EWT can decompose a signal according to its contained information. Based on the wavelet theory, the model overestimation problem can be resolved by EWT. Hence, the EWT has more applications than wavelet transform and EMD. It is worth introducing the EWT into the compound faults decoupling to provide better detection performance than the wavelet transform and EMD based methods [26,27].

On the other hand, complicated post-treatment is required for the decoupled sub-signals in previous publications [18–23] to determine each single fault of the compound faults. Strong expertize knowledge is involved with the single fault determination. The chaotic oscillator is an efficient technique to detect fault information in the post-treatment [28–30]. Wang et al. [28] showed that the duffing oscillator was very effective in weak signal detection. Guan et al. [29] used the duffing oscillator to identify the bearing faults. If the parameters of the duffing oscillator are properly set, a slight requirement on expertize knowledge is requested for the engineers. Hence, it is suitable to adopt duffing oscillator in practical applications to detect rolling bearing faults.

In order to decouple compound faults in the rolling bearings, a new method based on the empirical wavelet transform (EWT) and duffing oscillator is proposed in this paper. In this new method, the vibration signal of the rolling bearings is firstly adaptively decomposed into different modes by the EWT. The intrinsic characteristics of different single faults can be contained in different modes. Subsequently, by passing these EWT modes through properly designed duffing oscillators, each single fault can be identified according to the chaotic motion of the response of the duffing oscillator. Thus, the decoupling detection of compound faults can be achieved. Because the chaotic motion can be directly observed from the response of the duffing oscillator, the engineers do not have to acquaint significant knowledge about the chaos theory. Experiment tests were carried out in this paper to evaluate and verify the performance of the proposed EWT-duffing oscillator approach for compound faults decoupling diagnosis of rolling bearings. The results were compared with wavelet transform and EMD.

2. The proposed method for compound faults detection

In this work a new method for compound faults of rolling bearings is proposed based on empirical wavelet transform (EWT) and duffing oscillator. The recent publications [24] demonstrate that the EWT is able to adaptively decompose a signal into intrinsic modes based on the information contained in the signal while the EMD produces model overestimation problem. Since the compound faults characteristics are coupled with each other in both time and frequency