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# Virtual prototype and experimental research on gear multi-fault diagnosis using wavelet-autoregressive model and principal component analysis method

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A B S T R A C T

Gear systems are an essential element widely used in a variety of industrial applications. Since approximately 80% of the breakdowns in transmission machinery are caused by gear failure, the efficiency of early fault detection and accurate fault diagnosis are therefore critical to normal machinery operations. Reviewed literature indicates that only limited research has considered the gear multi-fault diagnosis, especially for single, coupled distributed and localized faults. Through virtual prototype simulation analysis and experimental study, a novel method for gear multi-fault diagnosis has been presented in this paper. This new method was developed based on the integration of Wavelet transform (WT) technique, Autoregressive (AR) model and Principal Component Analysis (PCA) for fault detection. The WT method was used in the study as the de-noising technique for processing raw vibration signals. Compared with the noise removing method based on the time synchronous average (TSA), the WT technique can be performed directly on the raw vibration signals without the need to calculate any ensemble average of the tested gear vibration signals. More importantly, the WT can deal with coupled faults of a gear pair in one operation while the TSA must be carried out several times for multiple fault detection. The analysis results of the virtual prototype simulation prove that the proposed method is a more time efficient and effective way to detect coupled fault than TSA, and the fault classification rate is superior to the TSA based approaches. In the experimental tests, the proposed method was compared with the Mahalanobis distance approach. However, the latter turns out to be inefficient for the gear multi-fault diagnosis. Its defect detection rate is below 60%, which is much less than that of the proposed method. Furthermore, the ability of the AR model to cope with localized as well as distributed gear faults is verified by both the virtual prototype simulation and experimental studies.



## 1. Introduction

As a key component of rotating machinery, gears are mostly subjected to progressive deterioration due to severe working conditions [1]. The condition of a gear will directly affect the normal running of the machine or even the entire

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system. The faults caused by gear failures account for 10% of the malfunctions in rotating machines and 80% in the transmission machinery, respectively. Therefore, it is necessary and critical that an early detection and diagnosis of gear faults be performed to prevent breakdown accidents and to minimize production loss.

To date gear fault diagnosis has received intensive study for several decades. Among the available diagnosis techniques, vibration analysis is manifestly the most commonly used method and also very efficient because vibration signals, which can be easily obtained by the means of accelerometers, carry important dynamic information of the machines. Considering that the early gear failure information is usually heavily corrupted by noise [2], a sensitive detection method for fault signature is needed. Most methods have sought to analyze the gear vibration signal in the time domain and/or the frequency domain. The time synchronous average (TSA) technique has been proven an effective tool in machine vibration monitoring and fault diagnosis [3–6]. It can remove the non-coherent and non-synchronous components, while preserving only the periodic components of the gear of interest by averaging the time signals of the particular gear over a large number of cycles [7,8]. The signal-to-noise ratio is improved accordingly, and the interferences from other stages of the gearbox can be reduced [7]. Zeroing the gear meshing harmonics from the TSA, the residual signal, which contains the fault signature, can be obtained for fault diagnosis [9,10]. Consequently, small gear faults can be detected well. Successful applications of the TSA based methods to detect earlier degradation of a gear tooth are abundant [3–10]. However, the TSA usually needs a phase reference signal provided by additional hardware, such as a tachometer or an encoder to keep all the averaged segments in phase. Otherwise, this method will suffer from the period estimation error and fail to work [7,8]. More importantly, when dealing with different combinations of faults on more than one gear, the TSA has to be carried out several times with reference to the rotations of different gear shafts. This is because the TSA only represents an estimation of the average meshing vibration of the gear of interest, and the non-synchronous vibration from other gears and noise are averaged out. This inconveniency may make the TSA time consuming and increase its operational complexity for the detection of coupled gear faults. As a result, an effective method is needed to detect gear multiple faults (both single and coupled gear faults).

A time–frequency analysis offers an alternative method to signal analysis by presenting information in the time–frequency domain simultaneously. Classical representations include Wigner–Ville distributions (WVD) [11], empirical mode decomposition (EMD) [12,13] and wavelet transform (WT) [14,15], etc. Among the available vibration analysis methods, the wavelet transform [13] has particular advantages for characterizing signals at different localization levels in both time and frequency domains. Moreover, the WT can be performed directly on the raw vibration signals without the need to process the ensemble average of the signals [16]. Hence, fault detection can be conducted for every revolution, which simplifies the calculation and makes the diagnosis procedure faster. Geng and Qu [17] used the wavelet packet technique for the mechanical fault diagnosis and proved that the wavelet was more effective than the conventional methods. Unfortunately the wavelet technique they used had some disadvantages including the problem of wavelet function selection. In order to overcome the limitation of orthogonal wavelet transform, the continuous wavelet transform (CWT) was introduced into the gearbox diagnosis [6,18]. However, the wavelet still had some inevitable drawbacks such as the requirements of constructing the mathematical model and studying the fault mechanism of the system of interest [13,14]. In addition, due to the limited number of scales the wavelet was not self-adaptive in nature so it had difficulties describing all details of the signal [13]. Although Lin and Qu [14] developed an adaptive wavelet filter based on Morlet CWT to enhance the feature extraction, their study was limited to the noise removal. A sound gear fault detection method was not proposed and developed in their study. Consequently, it was ineffective to use the WT technique to detect and analyze gear multiple faults. Intelligent artificial neural networks (ANN) classifiers [11,15], therefore have been combined with the WT technique for the gear multi-fault diagnosis. Although they give a satisfactory performance on the identification of gear multiple faults, the intelligent algorithms are time consuming because of the large amount of calculations involved. In addition, it is not easy to figure out how the neural networks function.

In comparison, the Autoregressive (AR) model is a practical method with simple calculations. It can extract the fault feature of the vibration signals effectively without a requirement of constructing a mathematical model and studying the fault mechanism of the system [13,19,20]. In addition, it is suggested that the autoregression parameters of AR model are very sensitive to condition changes [21,22] and thus the failure mode can be identified directly by analyzing these parameters [13,19,20]. However, the estimation of the autoregression parameters may not be available when the AR model is applied to dealing with the signals contaminated by strong noise and nonlinear components [19]. Therefore, it is essential that the raw vibration signals are preprocessed before using the AR model [13]. Since the WT is proven to be a successful tool for non-stationary signal de-noising, the integration of the WT and AR model may provide much better efficacy in the fault feature extraction and detection of vibration signals. Kotnik and Kacic [23] used the WT and AR based feature extraction method for speech signals. The noise robustness was improved with the application of the wavelet-based de-noising in their work. Li et al. [24] successfully combined the wavelet transform with the AR model for monitoring and analyzing interharmonics in a power system, and the test results showed that the wavelet-AR model method was able to detect the interharmonics near the integer harmonics accurately under a poor signal-to-noise ratio. For gear fault diagnosis, Zhou et al. [2] presented the wavelet-AR model method to diagnose gearboxes. They used the wavelet transform as a de-noising filter for the original signal to obtain fault signals, and then the fault type was identified by the AR model spectrum estimation method. The limitation of the study is that only two operating conditions, that is, normal and cracked, were investigated in their research. The validity of the approach and outcomes should be further tested for different fault degrees or multi-fault conditions.