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Bearing fault diagnosis using a whale optimization algorithm-optimized orthogonal matching pursuit with a combined time–frequency atom dictionary

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A B S T R A C T

Condition monitoring and fault diagnosis of rolling element bearings are significant to guarantee the reliability and functionality of a mechanical system, production efficiency, and plant safety. However, this is almost invariably a formidable challenge because the fault features are often buried by strong background noises and other unstable interference components. To satisfactorily extract the bearing fault features, a whale optimization algorithm (WOA)-optimized orthogonal matching pursuit (OMP) with a combined time–frequency atom dictionary is proposed in this paper. Firstly, a combined time–frequency atom dictionary whose atom is a combination of Fourier dictionary atom and impact time–frequency dictionary atom is designed according to the properties of bearing fault vibration signal. Furthermore, to improve the efficiency and accuracy of signal sparse representation, the WOA is introduced into the OMP algorithm to optimize the atom parameters for best approximating the original signal with the dictionary atoms. The proposed method is validated through analyzing the bearing fault simulation signal and the real vibration signals collected from an experimental bearing and a wheelset bearing of high-speed trains. The comparisons with the respect to the state of the art in the field are illustrated in detail, which highlight the advantages of the proposed method.

1. Introduction

Rolling element bearings are widely used as the key machine parts of major equipment in various industrial fields. Due to the poor working conditions (e.g., heavy load and high running speed), the rolling element bearings are also one of the most vulnerable components of an equipment, and the consequences of bearing failure could range from breakdown maintenance to catastrophic accident [1,2]. Therefore, studies of the bearing condition monitoring and fault diagnosis have important theoretical and practical value in engineering.

It is an inescapable fact that the bearing vibration signals collected from the monitored machinery contain various interferences including background noises and other unstable components [3,4]. Thus, the main problem of bearing fault diagnosis is how to effectively remove interferences and extract the fault features. Numerous methods have been developed for this issue including traditional linear time–frequency representation methods [5,6], classical time–frequency distribution

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methods (nonlinear time–frequency representation methods) [7,8], and some advanced methods [9–11]. However, traditional linear time–frequency representation methods such as short-time Fourier transform and wavelet transform have many limitations [12,13]. (1) The signal representation results are not sparse or concise. (2) Because of the Heisenberg's uncertainty principle, these methods are often unable to achieve a satisfactory time–frequency resolution. The applications of Wigner–Ville distribution, Cohen's class time–frequency distributions and other nonlinear time–frequency representation methods are greatly restricted because of the inherent cross-interference items [13]. Some advanced methods such as empirical mode decomposition and local mean decomposition can self-adaptively decompose a complex signal to achieve feature extraction, but they are influenced by the end effect and mode mixing problem [14,15].

To achieve a more flexible, concise and adaptive representation of the signal, Coifman and Wickerhauser [16] proposed the concept of signal sparse decomposition. The main idea of signal sparse decomposition theory is that the basis functions are replaced by an overcomplete set of redundant functions known as atom dictionary or overcomplete dictionary, and the signal is represented as linear combinations of minority vectors in atom dictionary [16]. The process of using the atom dictionary to obtain the sparse representation of signal is known as the signal sparse decomposition. According to the sparse decomposition theory, the closer between the atom dictionary and signal's intrinsic structure, the sparser the signal decomposition results [17]. Consequently, the selection of atoms to construct the atom dictionary is an important research topic in signal sparse representation. Until now, researchers have constructed various dictionaries according to the properties of fault vibration signals and achieved favorable analysis results. For instance, Liu et al. [18] used the matching pursuit (MP) with time–frequency atoms to detect the localized defects of rolling element bearings. Zhu et al. [19] proposed an orthogonal matching pursuit (OMP) with pulse atoms based on the vibration model of faulty bearings for bearing fault detection. Cui et al. [20] constructed atom libraries based on the structured atoms for the MP of the gear vibration signals. Du et al. [21] developed a wind turbine gearbox fault diagnosis framework which used a union of redundant harmonic dictionary and overcomplete Gabor dictionary. Cui et al. [22] designed a novel MP method with a step-impulse dictionary based on the quantitative relationship between the time interval of the seemingly double impact actions and fault size. Qin [23] designed a family of model-based impulsive wavelets and used it as sparse representation for rolling element bearing fault diagnosis.

In addition, from the perspective of function approximation, sparse representation is a high degree of nonlinear approximation [24]. It is challenging to use a highly nonlinear method to approximate a given signal in an overcomplete set of functions [25]. Therefore, another important research topic is to design and improve the sparse decomposition algorithm. Several algorithms have been proposed such as FOCal Underdetermined System Solver [26], orthogonal best-basis methods [16], MP [27] and base pursuit [28]. Considering the sparsity measure function, sparsity of solution, computational speed and computational accuracy, MP is a more ideal and practical method [25], and thus it has been widely used in the field of machinery vibration signal analysis and fault diagnosis. However, MP has two main shortcomings: overmatching and nonorthogonal projection that affect its convergence rate. These two drawbacks are attributed to the redundancy of the overcomplete dictionary and greed characteristic of the MP algorithm. The OMP algorithm [29] successfully overcomes these two drawbacks by adding Schmidt orthogonalization. Although this approach increases the computational complexity of the algorithm, the convergence rate of OMP is faster than that of MP from the aspect of decomposition effect. Thus, in the case of the same sparse representation accuracy, the OMP algorithm selects fewer atoms; that is to say, the signal representation result is much sparser. To further improve the performance of sparse decomposition algorithms, many intelligent optimization algorithms including genetic algorithm (GA) [30], multipopulation GA [19] and particle swarm optimization (PSO) algorithm [31] were introduced into sparse representation and achieved more efficient and faster signal sparse decomposition.

Recently, a novel nature-inspired metaheuristic optimization algorithm termed whale optimization algorithm (WOA) is proposed by Mirjalili and Lewis [32]. In Ref. [32], Mirjalili and Lewis also verified the WOA's performance and superiority compared to PSO algorithm and gravitational search algorithm (and any other similar algorithms) by solving a set of mathematical optimization problems and more challenging real engineering problems. Although this algorithm was proposed recently, it has been successfully applied in many engineering fields. For instance, Mostafa et al. [33] proposed a method for the liver segmentation in magnetic resonance imaging images based on WOA. Prakash and Lakshminarayana [34] used WOA to determine the optimal sizing and placement of capacitors for a typical radial distribution system.

Based on the above introduction, a WOA-optimized OMP with a combined time–frequency atom dictionary for bearing fault diagnosis is proposed in this paper. Firstly, the combined time–frequency atom dictionary whose atom is a combination of Fourier dictionary atom and impact time–frequency dictionary atom is designed according to the properties of bearing fault vibration signal. Furthermore, the WOA algorithm is introduced into the OMP algorithm to select the optimal atoms matching with the residual signal during the iterations, thus improving the efficiency and accuracy of signal sparse representation.

The rest of this paper is organized as follows. Section 2 introduces the proposed method and the relevant background theories. In Section 3, simulation signal analysis and comparisons with other method are carried out. In Section 4, experimental verification and engineering application are conducted. Also in this section, the comparisons with the GA-optimized MP (GA-MP) with Gabor atom dictionary and the fast kurtogram method are carried out. Finally, the conclusions are drawn in Section 5.