Mechanical Systems and Signal Processing 118 (2019) 645–657

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

A new adaptive evolutionary digital filter based on alternately evolutionary rules for fault detection of gear tooth spalling

Liming Wang [a], Weijun Ye [a], Yimin Shao [a,*], Huifang Xiao [b]

[a] State Key Laboratory of Mechanical Transmission, Chongqing University, Chongqing 400030, PR China
[b] National Engineering Research Center of Flat Rolling Equipment, University of Science and Technology Beijing, Beijing 100083, PR China

ARTICLE INFO

Article history:
Received 17 June 2017
Received in revised form 27 August 2018
Accepted 3 September 2018

Keywords:
Fault diagnosis
Gear tooth spalling
Evolutionary digital filter (EDF)
Adaptive noise cancellation (ANC)

ABSTRACT

Evolutionary digital filter (EDF) is an adaptive filter that controlled by adaptive algorithm based on the evolutionary strategies: cloning and mating. The adaptive algorithm of EDF exhibits the advantage of avoiding local optimum problems that arise from a multiple-peak performance surface of an adaptive noise cancellation (ANC) system. However, the convergence rate of the classic EDF is limited by inappropriate arrangement of evolutionary strategies and large population of individuals. In this paper, a new method referred to alternately evolutionary digital filter (AEDF) is proposed in order to solve the problem of lower convergence rate of the classic EDF. The basic concept of the proposed method is to alternately apply mating evolutionary strategy to locate the peaks in performance surface quickly and then apply cloning evolutionary strategy to get the global optimum near the peaks accurately. The convergence rate and noise cancellation performance of the proposed method is verified by both simulated signals and experimental signals. The results show that the proposed AEDF-based ANC method can effectively detect the gear tooth spalling faults in noisy environment and exhibits much faster convergence rate compared to previous methods.

1. Introduction

In the fault diagnosis of rotating machinery, e.g. gearbox or bearing, the faulty signals are inevitably masked by background noise or interference signals generated by other normal mechanical components, which increase the difficulty to extract the faulty features for effective and accurate diagnosis, especially at the early stage of the fault [1–5].

Proposed by Widrow [6], ANC is proven to be an useful technique to remove additive noises from the contaminated raw signals and has been successfully applied in electrocardiogram (ECG) signals de-noising, speech recognition as well as fault diagnosis of machinery [7–10]. The basic concept behind ANC is to identify or design an adaptive filter to optimally estimate the noise according to the reference signal and subtract it from the primary noisy signal [11]. As a gradient steepest descent method, the least mean squares (LMS) algorithm requires fewer computational resources and easy to program, thus the LMS and its improved algorithms are commonly used to find the optimal filter coefficients for ANC. For example, Liang et al. presented a combined method for railway wheel flat and rail surface defect detection, unwanted interferences are reduced by ANC based on the LMS algorithm, and thus the weak signals are extracted from strong background noises [10]. Ibrahim developed a modified LMS algorithm for enhancing condition features of a two stage gearbox, different levels of gear tooth

* Corresponding author.
E-mail address: ymshao@cqu.edu.cn (Y. Shao).

https://doi.org/10.1016/j.ymssp.2018.09.005

breakage faults are detected successfully [12]. Tian introduced the application of kernel-LMS algorithm to find the optimal filter for nonlinear interference cancellation, and it is successfully used for planetary gearbox fault feature enhancement [13]. Dhiman described the comparisons between LMS, normalized-LMS, time varying-LMS, recursive least square, fast transversal recursive least square, both their computational complexity and signal-to-noise ratio are examined and discussed [14]. However, the gradient-based LMS algorithm can be easily stuck at local minimum because the performance surface of the adaptive filter is generally multimodal with respect to the filter coefficients [15].

Aiming to solve the local minimum problem of LMS, Abe et al. proposed the EDF method, which is a population-based method that based on the evolutionary strategies of living things: cloning and mating. It consists of many linear/time-variant inner filters which are treated as individuals. The variation of the coefficients of inner filters (individuals) in EDF is controlled by using the evolutionary strategies. The EDF method is a non-gradient and multi-point search algorithm, thus it is not susceptible to local minimum problems that arise from a multimodal performance surface. Besides, it has been proven that the EDF achieves smaller adaptation noise than other algorithms, e.g. the LMS based adaptive digital filter and the simple genetic algorithm based adaptive digital filter [16–19]. Though EDF method settle the problem of local minimum, the convergence rate of the classic EDF is restricted by cloning evolutionary strategy which is time consuming. Zhou and Shao presented a beehive pattern evolutionary digital filter (BP-EDF) method, which enhances the spread of information among individuals based on the beehive structure cell and the random search ability of the classic EDF, thus the convergence speed is improved in some degree [20]. Xiao et al. introduced an improved simplex-based adaptive evolutionary digital filter for bearing fault diagnosis. A new evolutionary strategy of mutating method based on simplex optimization method is presented to enhance the ability of the classic EDF to adapt to the changing environment [21]. However, in both the classic EDF method and its improved methods, the cloning evolutionary strategy and mating evolutionary strategy are carried out simultaneously, there is no effective criteria to guarantee the individuals ready for cloning are near to the peaks of the multimodal performance surface, which may lead to the waste of computational resources and low convergence rate of the algorithm. In this paper, an improved adaptive evolutionary digital filter based on alternately evolutionary rules is proposed. In AEDF, a new arrangement of cloning evolutionary strategy and mating evolutionary strategy is established to guarantee the individuals ready for cloning are near to the peaks of the multimodal performance surface. Both the simulated results and experimental results show that the AEDF achieves much faster convergence rate than other methods.

The rest of the paper is organized as follows: Section 2 describes the adaptive rules of the classic EDF briefly and then introduces the adaptive noise cancellation based on the proposed AEDF method; the convergence performance and noise cancellation performance of AEDF are validated by both simulated signal and experimental signal in Sections 3 and 4, respectively. Conclusions are drawn in Section 5.

2. Adaptive noise cancellation based on AEDF

2.1. Preview of the adaptive rules of EDF

The EDF, as mentioned before, is an adaptive filter which is controlled by adaptive algorithm based on the evolutionary strategies: cloning and mating. It consists of many linear/time-variant inner digital filters which correspond to individuals. The adaptive algorithm of EDFs controls and changes the coefficients of each individual (inner digital filter) using the cloning and mating evolutionary strategies [17].

Fig. 1 illustrates the adaptive rules of EDF from jth generation to $(j+1)^{\mathrm{th}}$ generation. There are 4 steps in the adaptive rules of EDF:

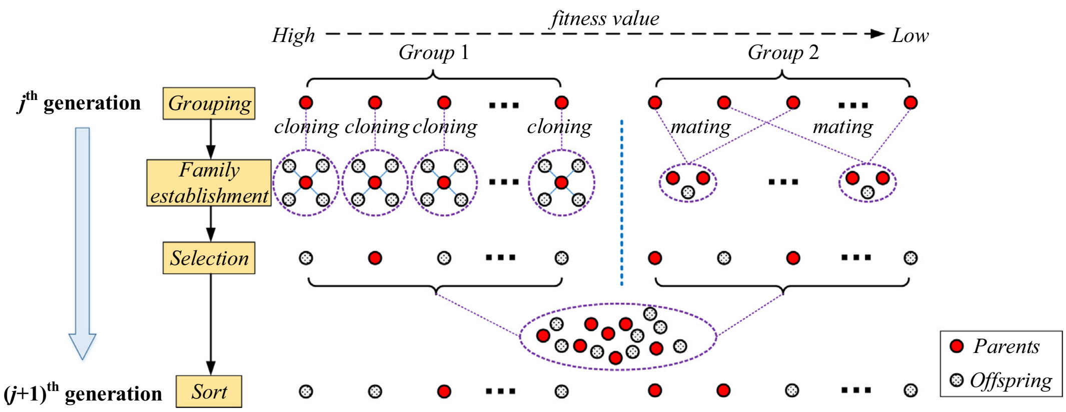

Fig. 1. Schematic plot of adaptive rules of the classic EDF.