Mechanical Systems and Signal Processing 84 (2017) 15–38

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

A sensor network based virtual beam-like structure method for fault diagnosis and monitoring of complex structures with Improved Bacterial Optimization

H. Wang, X.J. Jing *

Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hong Kong, and Hong Kong Polytechnic University Shenzhen Research Institute, Shenzhen, China

ARTICLE INFO

Article history:
Received 3 November 2015
Received in revised form
20 June 2016
Accepted 2 July 2016

Keywords:
Fault diagnosis
Virtual beam
Bacterial colony optimization
Structures

ABSTRACT

This paper proposes a novel method for the fault diagnosis of complex structures based on an optimized virtual beam-like structure approach. A complex structure can be regarded as a combination of numerous virtual beam-like structures considering the vibration transmission path from vibration sources to each sensor. The structural 'virtual beam' consists of a sensor chain automatically obtained by an Improved Bacterial Optimization Algorithm (IBOA). The biologically inspired optimization method (i.e. IBOA) is proposed for solving the discrete optimization problem associated with the selection of the optimal virtual beam for fault diagnosis. This novel virtual beam-like-structure approach needs less or little prior knowledge. Neither does it require stationary response data, nor is it confined to a specific structure design. It is easy to implement within a sensor network attached to the monitored structure. The proposed fault diagnosis method has been tested on the detection of loosening screws located at varying positions in a real satellite-like model. Compared with empirical methods, the proposed virtual beam-like structure method has proved to be very effective and more reliable for fault localization.

1. Introduction

Fault diagnosis has been attracting increasing attentions in the mechanical engineering to monitor the operational condition of machines and isolate the unpredicted structural faults. Generally, the techniques for fault diagnosis can be simply divided into model-based fault diagnosis and model-free fault diagnosis [1].

Model-based fault diagnosis is frequently studied by using sensor networks to extract the physical features of the structures [1–3]. This group of methods would be accurate if the physical information of the structure is well-defined [4]. Considering the deficiency of model-based fault diagnosis techniques that the performance of the fault diagnosis highly depends on the accuracy or quality of model through the assumption that detailed numerical model of structure is satisfied [5–7], it is not appropriate to employ the model-based methods for on-line application, especially for time varying dynamic complex systems. For model-free fault diagnosis methods, it is more flexible since no dependence on specific structure, while relies on the signals measured from closed loop experiments [8].

Among model-free fault diagnosis methods, mostly, vibration-based damage identification methods are employed for

* Corresponding author.
E-mail address: mmjxj@polyu.edu.hk (X.J. Jing).

http://dx.doi.org/10.1016/j.ymssp.2016.07.003
0888-3270/

global fault diagnosis of structures. The data measured by vibration sensors are originally time series data. The needs for fault diagnosis of complex structures have brought an increasing research studies on time series analysis. The noise as well as the wide spectrum of defect signals increase the difficulty in fault diagnosis using time domain vibration signals directly [9]. For that, characteristic features are proposed to extract the most desired features of signals which are relevant to health condition of the system. Those features can be simply divided into time domain features, frequency domain features, and time-frequency domain features [10,11]. To be simple and interpretable, the main advantage of all the time domain-features is to avoid complexity of the preprocessing since they do not need the laborious tasks of framing, windowing, filtering, Fourier transformation, etc. [12], which brings the wild application of time domain features [9,10,12–16]. Frequency domain features, e.g. Fast Fourier Transformation (FFT), are transformed from time domain data to isolate the fault at certain frequency components [17], which enables the popular application of frequency domain features for fault diagnosis [18–20]. Time frequency domain features, e.g. wavelet transformation (WT), are capable of treating non-stationary signals which frequency domain features are less robust [21–24]. Even so, the effectiveness of features have to confront with high computational cost, especially in dealing with high dimensional time series data. In such circumstances, time domain features are considered to extract the characteristic features of time series using certain segments.

Another challenge is that few approaches are applicable if available prior knowledge of the fault system is limited. Currently, it is so popular to develop a fault diagnosis technique in cooperation with classification and identification processes [25–28]. Therefore, there is a demand for techniques that can detect the health condition of the system without the requirement of various candidate samples for training.

In this paper, a virtual beam-like structure method based on a biologically inspired optimization method is proposed for fault diagnosis of complex structures with bolted-base hanging components. The structure is studied using acceleration sensor networks, and the vibration energy transmission paths from the vibration source to sensors are exploited and regarded as 'virtual beams'. The occurrence of a fault brings changes of vibration energy along some transmission paths (virtual beams), which are manifested as changes in signals from sensors along the corresponding energy transmission paths. These transmission paths are conceptualized as 'virtual beams' that can be automatically constructed by an improved biologically inspired optimization method and consequently used for fault localization. The main contributions of this paper are as follows:

1) A virtual beam-like structure method is proposed for the fault diagnosis of complex structures with less or no requirement for prior fault knowledge of the system.
2) A biologically inspired optimization method based on bacterial algorithm is improved for handling the combinatorial problem associated with feature selection.
3) The construction of the 'virtual beam' is formulated as an optimization problem of feature selection and is optimized automatically by the improved bacterial based optimization algorithm for fault localization.
4) The proposed fault diagnosis approach needs only the analysis of vibration-based time domain data regardless of frequency range or natural frequency of the studied structure.
5) The proposed fault diagnosis system is applicable to general structures in mechanical engineering, and not confined to a specific type.

A generalized comprehensive fault detection and localization system based on intelligent optimization method and virtual beams is developed in this study to monitor the health condition of complex structures in various mechanical engineering systems with attached sensor networks.

The rest of this paper is organized as follows. In Section 2, the principle of the intelligent optimization are presented, and the effectiveness of the improved optimization is demonstrated on benchmarks. Section 3 provides the signal preprocessing, the concept and construction of 'virtual beam', as well as the summary of virtual beam-like structure method for fault detection. Afterward, the application of the proposed virtual beam-like structure method on complex structures (i.e. a real satellite-like model) is demonstrated and discussed in Section 4. Finally, Section 5 concludes the paper and provides the outlook for future work.

2. Improved Bacterial Optimization Algorithm

Inspired by the foraging or chemotaxis processes of *Escherichia coli* bacteria, Bacterial Foraging Optimization (BFO) [29] and Bacterial Chemotaxis (BC) [30] are two earliest bacterial based algorithms for optimization problems. These two algorithms are credited with starting a new heuristic family in computational intelligence and provide a global searching capability for control and optimization. Since their advent, several Bacterial Algorithms (BAs) and extensions to them have been applied in research areas such as fault detection [31,32], signal processing [33–35], and pattern recognition [36,37].

However, one of main disadvantages associated with BAs is the expensive computational time needed for conducting the global search for the best solutions. The embedded interior circulation renders it impossible to solve the high dimensional problems arising while analyzing on-line systems. Many strategies have been applied to overcome this drawback. Among these, Bacterial Colony Optimization (BCO) [38] is the only method (to the best of our knowledge) capable of improving the search capability, fundamentally on the basis of the bacterial life-cycle, by adopting the conditional behavior modes. This