Mechanical Systems and Signal Processing 66-67 (2016) 557–567

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

A novel identification method of Volterra series in rotor-bearing system for fault diagnosis

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ARTICLE INFO

Article history:
Received 19 June 2013
Received in revised form
7 March 2015
Accepted 4 May 2015
Available online 26 May 2015

Keywords:
Volterra series
Fault diagnosis
KK-PSO
Rotor-bearing system

ABSTRACT

Volterra series is widely employed in the fault diagnosis of rotor-bearing system to prevent dangerous accidents and improve economic efficiency. The identification of the Volterra series involves the infinite-solution problems which is caused by the periodic characteristic of the excitation signal of rotor-bearing system. But this problem has not been considered in the current identification methods of the Volterra series. In this paper, a key kernels-PSO (KK-PSO) method is proposed for Volterra series identification. Instead of identifying the Volterra series directly, the key kernels of Volterra are found out to simply the Volterra model firstly. Then, the Volterra series with the simplest formation is identified by the PSO method. Next, simulation verification is utilized to verify the feasibility and effectiveness of the KK-PSO method by comparison to the least square (LS) method and traditional PSO method. Finally, experimental tests have been done to get the Volterra series of a rotor-bearing test rig in different states, and a fault diagnosis system is built with a neural network to classify different fault conditions by the kernels of the Volterra series. The analysis results indicate that the KK-PSO method performs good capability on the identification of Volterra series of rotor-bearing system, and the proposed method can further improve the accuracy of fault diagnosis.

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1. Introduction

Fault diagnosis of rotor-bearing system is essential to prevent dangerous accidents and improve economic efficiency. As a hot research topic, it has been studied by many academics, and most of the methods can be separated into two major categories: signal processing method and modeling method [1]. As the modeling method has favorable performance in considering the parameters characteristic of different rotor-bearing system, it has gained attractive and wide attention.

The critical problem of modeling method is the determination of the mathematical structure of a physical system from input–output measurement [2]. As a mature theory, linear ARMA model has been employed for fault diagnosis in rotor-bearing system [3–5]. But the ARMA model doesn't have a good performance in the description of the dynamic behavior of the rotor-bearing system, because there are many nonlinear factors which may cause nonlinear vibration, such as the stiffness and damping.

With the development of the nonlinear theory, Volterra series has been widely applied in the modeling and faults diagnosis of nonlinear system. The multidimensional Fourier transformation of the Volterra kernels which is defined as the

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http://dx.doi.org/10.1016/j.ymssp.2015.05.006
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generalized frequency response function (GFRF) has been widely employed in the analysis of nonlinear system [6,7]. The GFRF can describe the nonlinear response effectively in the frequency domain. But the high-dimensional GFRF has less performance in the way of intuitive, and GFRF always encounter the problem of disaster of dimensionality. Nonlinear Output Frequency Response (NOFRFs) as a transformation of GFRF has gained attractiveness of many researchers [8–11]. The NOFRFs provide a simple description of the frequency domain behaviors of nonlinear system, and it has a very good performance in fault diagnosis. But this method needs multi sinusoidal excitation in the same frequency and different amplitude. The excitation limitation makes troublesome in operation and online fault diagnosis. The time-domain Volterra series has intuitive in its structure, and it is useful for online fault diagnosis. The time-domain Volterra series will also encounter the problem of disaster of dimensionality. So, there is an urgent demand for effective identification methods.

Many identification methods have been proposed for the Volterra series of rotor-bearing system [1,12–19]. A blind quadratic modeling method based on HOS was proposed to detect the mechanical fault [5]. A LMS variant method was used to estimate second-order Volterra system parameters from noisy measurements [12]. These classical identification methods transform the input-output signal into the matrix form, and the Volterra's kernels is identified with the least squares method. But the input signal of rotor-bearing system is a periodic signal. The undetermined characteristic leads to the traditional identification method inefficiency. Some intelligent identification methods have also been employed. Genetic algorithm (GA) was used to identify the Volterra kernels for fault diagnosis [1]. Yang et al. used particle swarm optimization (PSO) to identify the Volterra series [13]. Although these intelligent methods approach the model well, the result of identification is not unique. So there is an urgent need to develop a new identification method that considers the periodic input signal for the Volterra series of rotor-bearing system.

In this paper, a key kernels-PSO (KK-PSO) method is proposed to identify the Volterra series of rotor-bearing system. Instead of identifying the Volterra series with intelligent methods directly, the influence of each kernel of the Volterra series is calculated firstly. Then, the key kernels are found to simplify the Volterra series. Next, the Volterra series is identified by the PSO method. The new method is compared with orthogonal least squares method and traditional PSO method through simulation verification. The results show that the KK-PSO is accurate and reliable. Finally, the proposed method is applied to identify the Volterra series of a rotor-bearing test rig. And fault classification is further done on the test rig with a neural network.

The rest of this paper is organized as follows: A brief introduction of the problem in identification of the Volterra series is described in Section 2. In Section 3, the KK-PSO method for identification of the Volterra series is presented and fault diagnosis method by kernels classification with neural network is also introduced. Simulation verification and experimental tests on rotor test rig are present in Section 4. Finally, conclusions from this research as well as the advantages and limitations of the proposed method are discussed in Section 5.

2. Statement of problems

In real world, many engineering problems represent nonlinear behavior. Most nonlinear models in engineering and science can be described by a second order Volterra series [5].A single input signal output (SISO) Volterra series is considered as follows:

$$\mathbf{y}(n)=\sum_{l_0=0}^{M-1}\mathbf{h}_1(l_0)\mathbf{u}(n-l_0)+\sum_{l_1=0}^{M-1}\sum_{l_2=0}^{M-1}\mathbf{h}_2(l_1,l_2)\mathbf{u}(n-l_1)\mathbf{u}(n-l_2) \tag{1}$$

where $\mathbf{u}$ is the input signal, $\mathbf{y}$ is the output signal, M represents the memory length, $\mathbf{h}$ denotes the kernels of the system.

In order to express Eq. (1) in concise modality, the kernels $\mathbf{h}$ and input $\mathbf{u}$ are expanded into $\mathbf{H}$ and $\mathbf{U}(n)$, and $\mathbf{H}$, $\mathbf{U}(n)$ can be defined as:

$$\begin{aligned}\mathbf{H}=\big[&\mathbf{h}_1(0),\mathbf{h}_1(1),\ldots,\mathbf{h}_1(M-1),\ \vdots\ \mathbf{h}_2(0,0),\mathbf{h}_2(0,1),\ldots,\mathbf{h}_2(0,M-1),\\&\mathbf{h}_2(1,1),\ldots,\mathbf{h}_2(M-1,M-1)\big]^T\end{aligned} \tag{2}$$

$$\begin{aligned}\mathbf{U}(n)=\Big[&\mathbf{u}(n),\mathbf{u}(n-1),\ldots,\mathbf{u}(n-(M-1)),\ \vdots\ \mathbf{u}(n)^2,\mathbf{u}(n)\mathbf{u}(n-1),\ldots,\\&\mathbf{u}(n)\mathbf{u}(n-(M-1)),\mathbf{u}(n-1)^2,\ldots,\mathbf{u}(n-(M-1))^2\Big]\end{aligned} \tag{3}$$

$\mathbf{H}$, $\mathbf{U}(n)$, can be separated into two parts: The first order part and second order part. The dimension of $\mathbf{H}$ and $\mathbf{U}(n)$ is $(M^2/2+3M/2)\times 1$. Then, Eq. (1) can be described as the following matrix form:

$$\mathbf{y}=\mathbf{U}\times\mathbf{H} \tag{4}$$

Obviously, after expanding the input matrix and kernels matrix, the Volterra series can be considered as a linear model.

Many algorithms have been employed for identification of the Volterra series for example, ordinary least square (OLS), least mean square (LMS), recursive least square (RLS), as well as some evolution algorithms such as genetic algorithms (GAs), ant colony algorithm (AC), differential evolution (DE), and particle swarm optimization (PSO), etc. Most of these algorithms consider $\mathbf{u}$ as a Random process or Gaussian Random process, but the input signal $\mathbf{u}$ in rotor-bearing system is a periodic signal. Then the input matrix $\mathbf{U}$ is a singular matrix, which leads to the identification of the Volterra model

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