Journal of Sound and Vibration 411 (2017) 210–231

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

An adaptive proper orthogonal decomposition method for model order reduction of multi-disc rotor system

Yulin Jin [a,*], Kuan Lu [a], Lei Hou [a,b,**], Yushu Chen [a]

[a] School of Astronautics, Harbin Institute of Technology, Harbin 150001, PR China
[b] School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, PR China

A R T I C L E I N F O

Article history:
Received 14 May 2016
Received in revised form 25 August 2017
Accepted 3 September 2017

Keywords:
POD method
Reduced-order models
Parameter robustness
Grassmann manifold
Rotor-bearing system

A B S T R A C T

The proper orthogonal decomposition (POD) method is a main and efficient tool for order reduction of high-dimensional complex systems in many research fields. However, the robustness problem of this method is always unsolved, although there are some modified POD methods which were proposed to solve this problem. In this paper, a new adaptive POD method called the interpolation Grassmann manifold (IGM) method is proposed to address the weakness of local property of the interpolation tangent-space of Grassmann manifold (ITGM) method in a wider parametric region. This method is demonstrated here by a nonlinear rotor system of 33-degrees of freedom (DOFs) with a pair of liquid-film bearings and a pedestal looseness fault. The motion region of the rotor system is divided into two parts: simple motion region and complex motion region. The adaptive POD method is compared with the ITGM method for the large and small spans of parameter in the two parametric regions to present the advantage of this method and disadvantage of the ITGM method. The comparisons of the responses are applied to verify the accuracy and robustness of the adaptive POD method, as well as the computational efficiency is also analyzed. As a result, the new adaptive POD method has a strong robustness and high computational efficiency and accuracy in a wide scope of parameter.

1. Introduction

The model order reduction of high-dimensional complex systems, attracting researchers' attention in many different engineering fields, has become one of central issues in dynamical system and control theory. The order reduction methods include center manifold method, Lyapunov-Schmidt method, inertial manifold method, approximate inertial manifold method, nonlinear Galerkin method, and POD method, etc. Among them, the POD method aims at obtaining the most important components of an infinite-dimensional continuous system or a finite high-dimensional DOFs system by using a few proper orthogonal modes (POMs). Hence, POD method can dramatically reduce the DOFs of a complex system to improve the computational efficiency, and maintain the high accuracy as well [1]. As a consequence, it is widely applied in a variety of areas, such as fluid mechanics [2–4], signal processing [5,6], image processing [7], optimal design [8,9], structure dynamics [10–15], chemical reaction control [16] and ocean engineering [17].

* Corresponding author.
** Corresponding author. School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, PR China
E-mail addresses: jinyl@hit.edu.cn (Y. Jin), houlei@hit.edu.cn (L. Hou).

http://dx.doi.org/10.1016/j.jsv.2017.09.001
0022-460X/

However, the reduced-order models (ROMs) obtained by the POD method usually lack robustness when the system parameters change [18]. In principle, the POMs with a new parameter value should be reconstructed, but it is too expensive to calculate the responses of a complex system for each new set of parameter, consequently it loses order reduction significance when the direct ROM (D-ROM) is constructed at every parameter value. To circumvent the parametric robustness problem, some modified POD methods were proposed, such as global POD method [20–23], local POD method [24–27], and adaptive POD method [28–36].

The global POD method is to enrich a snapshot set which contains the corresponding responses of different parameters in a parametric region. The set covers the global POD modes of integral parametric region, and then the ROMs will be obtained by the global-POMs [20–22]. This method is easy to perform, however, the proper positioning is required prior in the parametric domain. There is no theoretical or even empirical guidance to define proper parameter positioning, as well as multiple solutions may exist in a parametric domain for a strongly nonlinear system, and the comparatively accurate ROM needs to be obtained by many POMs [23]. But in many cases, this method is demonstrated unreliable and the optimal approximation characteristic is lost [33,37–40].

The local POD method, as its name suggests, is a local model order reduction method, and the parametric domain is divided into many subdomains, where the traditional POD method is applied. The POMs are constructed by the snapshot signals of local-parameter domains, and the equations of the original system are projected onto the subspace spanned by the local POMs, then the local ROMs are obtained. Repun and Vega [24] combined the POD and Galerkin method to study two one-dimensional parabolic equations (non-autonomic Fisher-like equation and Ginzburg-Landau equation), and the robustness of the method in local-parametric domain was proved numerically. The two-dimensional lid-driven cavity flow problem was investigated by Terragni and Valero [25] based on the local POD method, the computational cost was reduced significantly in contrast to computational fluid dynamics (CFD) method, and it is reliable for a certain scope of parameter. Compared with the global POD method, the local POD method not only guarantees the accuracy of the ROMs but also reduces the DOFs of the system further. However, this method may not obtain a smooth approximate solution from one sub-parametric domain to another, as well as the robustness and application area of this method are not proved rigorously at present [25,27].

The adaptive POD methods have relatively better robustness to the global and local POD methods. These methods update the POMs of ROM to get an optimal approximation model of each parameter in a parametric domain. A variety of adaptive POD methods were proposed in recent ten years, for example, the proper orthogonal mode interpolation (POMI) method [19,30,31], subspace angle interpolation (SAI) method [31–36], interpolation tangent space Grassmann manifold (ITGM) method [37–44] and other adaptive POD methods [45,46].

POMI method adapts the ROMs associated with different values of the physical or modeling parameter to a new parameter value by linearly interpolating the precomputed POMs [19,30,31]. Although the method is simple, the POMs of ROM are orthonormal basis for each parameter value, while the POMs will lose the property of orthogonal normalization for a new parameter when calculated by some interpolation methods. Hence, sometimes we can't get an accurate ROM by the POMI method [30–32]. The SAI method, for the purpose of producing a linear variation in the angle between a pair of subspace planes, is based on the principal angles and principal vectors [30]. It has been successfully used in the aeroelastic ROMs for a complete F-16 configuration in various airstreams by Lieu [31–34]. However, the SAI approach is a low-order interpolation method, therefore, the ROM is inaccurate when the interval of two parameter values is large, or the calculation efficiency is fairly low when the two parameter values are closely in a parametric region [33,34,39,40]. ITGM method is based on some concepts and principles of differential geometry, which include Grassmann manifold, tangent space of a point on manifold and the computation of geodesic paths on manifold [37–44], and this method also involves interpolation as well. Amsallem [37–39] applied this method to study aeroelastic ROMs of F-16 as well as F/A-18 fighter aircraft at different attack angles and Mach numbers, and proved this approach is a high-order interpolation method, where it is equivalent to the SAI method in case of 2-points interpolation. However it is recognized that the tangent space of a point on manifold presents the local property, as a consequence, it is possible to be failure in a wide scope of parameter.

In this paper, a new adaptive POD method is proposed for adapting the changes of the precomputed ROMs in physical or modeling parameters. This method also depends on some notions and results from differential geometry, and the Lagrange interpolation approach is also involved here. Subsequently, it is applied to the model order reduction of high-dimensional nonlinear rotor-bearing system. In a wide scope of rotation speeds, this method is compared with ITGM method and the D-ROM for a corresponding parameter value to verify the efficiency, the accuracy and the parameter robustness. The remainder of this paper is organized as follows. The theory of the adaptive POD method based on Grassmann manifold is presented in Sec.2. A nonlinear rotor-bearing system with a pair of liquid-film bearings and pedestal looseness fault is described in Sec.3. Next, the proposed method is applied in Sec.4 to verify the adaptation of ROMs of the nonlinear rotor-bearing system for a new parameter. Finally, conclusion is offered in Sec.5.

2. Theory of the adaptive POD method based on Grassmann manifold

In this section, the basic theory of the adaptive POD method based on Grassmann manifold is discussed. Firstly, we briefly review the relevant concepts and mathematical principles for differential geometry in section 2.1. Secondly, the ITGM method is recommended in section 2.2. At last, the new adaptive POD method-IGM method is demonstrated in section 2.3.