Mechanical Systems and Signal Processing 86 (2017) 224–236

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

A mixed model reduction method for preserving selected physical information

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ARTICLE INFO

Keywords:
Model reduction
Frequency domain
Component mode synthesis

ABSTRACT

A new model reduction method in the frequency domain is presented. By mixedly using the model reduction techniques from both the time domain and the frequency domain, the dynamic model is condensed to selected physical coordinates, and the contribution of slave degrees of freedom is taken as a modification to the model in the form of effective modal mass of virtually constrained modes. The reduced model can preserve the physical information related to the selected physical coordinates such as physical parameters and physical space positions of corresponding structure components. For the cases of non-classical damping, the method is extended to the model reduction in the state space but still only contains the selected physical coordinates. Numerical results are presented to validate the method and show the effectiveness of the model reduction.

1. Introduction

In the design of many space structures, with the given satellite bus structure and payload structures, usually only those structure components that connect the payload structures to the satellite bus need to be designed. For remote sensing satellites, these structure components can be vibration isolators, bipods and other kinds of components for reducing the vibration transmission, attenuating the vibration, and releasing the thermal deformation. To achieve the best system performance, especially the dynamic performance, for ensuring the imaging quality and the attitude control performance, generally, the design of such components is modified frequently. A design for the dynamic performance relies on the dynamic analysis of the whole structure usually with the finite element (FE) method. As the finite element model of a large space structure most often has tens of thousands of degree of freedoms (DoFs), to enhance the computational efficiency and shorten the design time, the scale of the finite element model should be reduced significantly. In addition to the component design, dynamic experiments also often required a reduced order dynamic model for evaluating the dynamic performance of a structure design. In the experiment, vibrations at points of the connection components and key points on the structure are generally measured. If the measurement points are the same as the DoFs of a dynamic model, the design effect can be directly evaluated, and the model parameters can thus be updated directly via the experimental data [1,2]. Moreover, a reduced order dynamic model is also required for the purpose of implementing active control functions to the structure components [3], for instance, the control of active vibration isolators and active struts to realize required motions and /or attenuate vibrations at some key points on the payload structure. Apparently, all these applications require a significantly large scale reduction of the original finite element model and in the meantime keep the physical coordinates of these structure components.

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http://dx.doi.org/10.1016/j.ymssp.2016.10.008
Received 24 February 2016; Received in revised form 27 August 2016; Accepted 8 October 2016
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The method proposed by Guyan [4] may be the most simple and classical model reduction method. It is a static condensation method, and by adding more master DoFs to the model, its accuracy can be enhanced. After more than twenty years, O'Callahan [5] added the influence of the inertia term to the static reduction transformation and proposed the Improved Reduced System (IRS) method. Like the Guyan reduction, IRS method can also be relatively easy realized with commercial FE software [6]. Friswell et al.. [7] proposed the iterated IRS method and proved its convergence [8] for further enhancing the accuracy of the model reduction. By introducing the Neuman series and taking the influence of the inertia term, Yang et al. [9] developed an improved Guyan reduction method with higher accuracy. Based on the Guyan reduction, Salvini and Vivio [10] derived a condensed form of the mass matrix and thus obtained a reduced model with better accuracy.

Suarez and Singh [11] proposed a method of dynamic model condensation by transforming the generalized eigen-problem of the dynamic system into a standard eigen-problem. This method can be taken as an extension of the IRS to a higher order method. As the reduced model has to be solved for eigen-pairs in each iteration, the computation cost of this method is relatively high. With the sub-space iterative method, Qu developed a new dynamic condensation method [12], which does not need to solve the reduced model at every iterative step. The convergence of the method was also theoretically proved. Compared with the static reduction method, a dynamic reduction method can achieve higher accuracy and have more freedom in choosing the master and slave DoFs though it may cost more computation time. By a proper selection of the master and slave DoFs, the accuracy of the model reduction can be further improved [13].

As non-classical damping is widely applied in structures to attenuate vibrations, some effort has been devoted to the model reduction method of structures with non-classical damping. Rivera et al. [14] applied the Guyan reduction to the structure with non-classical damping and developed approaches of static model reduction in both the physical space and the state space. Since the influence of the inertia term is neglected, the accuracy of the proposed method is not high. However, such method can provide explicit expressions for the condensed mass, damping and stiffness matrix. This brings convenience to the later analyses and applications. A dynamic model reduction method in the state space was proposed in [15,16], which can avoid the complex calculation by making the reduction transformation matrix real. This method can achieve high accuracy but it does not provide explicit forms for the mass, damping and stiffness matrix in the physical space. The convergent speed of this method was improved by a modification to the method [17].

The approach of System Equivalent Reduction Expansion Process (SEREP) proposed by O'Callahan et al. [18] does not rely on the choice of master and slave DoFs by constructing the reduction transformation with the retained modal vectors. With the thus obtained condensed model, the modes that are selected from the modal analysis result with the original model can be accurately regained. To avoid the modal analysis with the original finite element model and thus increase the computation efficiency, Papadopoulos and Garcia [19] use the modal analysis results with the reduced model obtained by the Guyan reduction or the IRS method to construct the reduction transformation of the SEREP. Nevertheless, this requires that these model reduction methods should give modal vectors with high accuracy. This in turn puts restriction on the selection of master DoDs [20].

The Component Mode Synthesis (CMS) method itself is also a kind of model reduction method and the model reduction efficiency is decided by the number of retained modes. With the fixed-interface CMS method, the information at specified physical coordinates can be kept by defining the interface position where these physical coordinates locate. Cho et al. [21,22] combined the iterated IRS method with the CMS method together and proposed a model reduction method for the cases of non-damping and proportional-damping. This method can be applied to solve the eigen-problem of a large scale structure and keep the physical information at given positions on the structure. By truncating higher order modes and keeping their influence in the form of residual flexibility, Ref. [23] obtained reduced order substructure model with high accuracy. To reduce the number of interface DoFs, a new technique referred as local-interface reduction was proposed in Ref. [24].

The above work is all in the time-domain. Another approach is in the frequency domain as the frequency response is often used to describe the dynamic properties of a structure and it contains such important information as resonant frequencies, damping ratios and amplification factors. The frequency domain model reduction is widely studied in the area of automatic control [3]. As the purpose is only for getting a reduced order model, generally specified structure component's positions and parameters in the physical coordinates are not preserved. In the area of structure dynamics, as the frequency domain model reduction most often is for providing a relationship between the measured response and the numerically calculated result, and sometimes for updating the model parameters with the measured frequency response [25], the physical parameters of specified structure components are not explicitly provided by the reduced model.

As being discussed in Refs. [1,2], in many practical applications, especially when vibration tests and active vibration controls/isolations are involved, the retained physical coordinates are given in a reduced model, or in other words, there is actually no freedom in selecting the master and slave DoFs. Although for a mode based reduction model, its accuracy is not determined by the selection of master DoFs, the reduction transformation relies on the eigen-solutions of the original model. This is not only inconvenient to the design and dynamic analysis of structure components, but also not convenient to the realization of active control. A reduced order model obtained with the CMS method contains both physical and modal coordinates. However, in many circumstances, the reduced order model should only contain the retained physical coordinates for such purposes as updating the modal parameters with experimental data, actively controlling the vibrations at some specified points on a structure with noncollocated arranged actuators, establishing a unique relationship between the structure components' dynamic parameters and the structure's system dynamic characteristics, and etc. On the other hand, the frequency-domain model reduction not only requires the solution of eigen-problem of the original model but also does not preserve the physical parameters that should be kept for later applications.

In the present paper, a new model reduction method in the frequency domain will be developed for satisfying the above

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