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Boundary condition handling approaches for the model reduction of a vehicle frame

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ABSTRACT

In order to apply model reduction technique to improve the computational efficiency for the large-scale FEM model of a vehicle, this paper presents the handling approaches for three widely-used boundary conditions, namely fixed boundary condition (FBC), prescribed motion (PSM) and coupling (COUP), respectively. It is found that iterated improved reduction system (IIRS) reduction method tends to generate better reduction approximation. Guyan method is not sensitive to the sequence of reduction and constraint under FBC, and can thus provide flexibility in handling different boundary conditions for the same system. As for PSM, 'constraint first' is recommended no matter which reduction method is used, and then separate reduction models can be coupled to form a new model with relative small dofs. By selecting appropriate master dofs for model reduction, the coupled model based on reduced models could produce same results as the original full one.

1. Introduction

Vibration performance is one of the most important factors affecting vehicle purchase decision and customer satisfaction. Severe vibration not only deteriorates drive comfort but also damage the vehicle structure or cargoes. To satisfy the increasing needs for comfortable vehicle, and consequently have a large market share, car manufacture industry has made great efforts to improve the vibration characteristics of vehicle in the past decades. Numerical approaches have been widely adopted in the comfort and vibration analysis [1–3] due to the time and cost consideration. In most simulations, vehicles are assumed to be composed of rigid bodies interconnected with constraint elements, indicating that the vehicle structures are unlikely to deform during the normal operation. However neglecting the flexibility or elasticity of structures in the simulation may produce inaccurate results. To avoid the weakness of rigid model, Hu et al. [4] produced a set of 31 dofs model to represent the compliant base for a powertrain system and found that the powertrain system can induce a strong interaction with the "elastic" base, and the mounts have to be re-designed. Suh et al. [5] used a beam-element vehicle model to couple with a lumped-mass powertrain system to carry out multidisciplinary optimization. They used a combination of the decoupling of engine mode and the maximization of seat comfort as the object function. Tamarozzi et al. [6] compared the dynamics of rigid multi-body model and other flexible vehicle models, and found the effects of flexibility.

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FEM is a good approach to preserve the flexibility of structures. In classical FEM, the approximation becomes more accurate as the mesh is refined with smaller elements [7]. To date, a typical passenger car FEM model can consist of hundred thousands or even millions of elements, which means a very large number of degrees of freedom (dofs). As a result of this, the frequency or time domain calculations of the large-scale models may not be performed effectively. In addition, FEA iteration has to be carried out in some optimization [8] or real-time control [9,10]. Fast calculation is essential for these tasks. Therefore, an effective way which both preserves the flexibility of the structure and computing efficiency is necessary. Model reduction technique paves the way for accomplishing these requirements.

Generally speaking, model reduction methods aim to find a low-order model to approximate the behavior of the original high-order model. Various methods have been proposed by researchers in the past decades and can be briefly classified into three categories, which are model-based (or KM-based), modal-based and state-space based method, respectively. Model-based reduction, such as Guyan [11], dynamic condensation [12], improved reduced system (IRS), and system equivalent reduction expansion process (SEREP) [13], intends to develop a condensation matrix to build the relationship between the retained dofs and the eliminated dofs. By utilizing the condensation matrix, the original higher-order ODEs corresponding to all coordinates can be converted to low-order ODEs for the retained coordinates. The reduced model is still defined in the displacement space, and the second-order structure of the system is preserved. These characteristics make the model-based reduction method very suitable for vibration analysis. The Guyan method uses static transformation matrix for reduction procedure. The inertial effect of the slave dofs is neglected, and therefore for high frequency this method becomes inaccurate. Dynamic condensation method utilizes dynamic stiffness instead of static stiffness, at a particular frequency to construct the transformation matrix. As such, some inertial effect is induced. In the use of SEREP, the eigenvalue problem of the full model should be calculated firstly. The reduction model by this method can precisely preserve the desired eigenvalues and eigenmodes of the full system. However it has some intrinsic disadvantages (such as matrix rank deficiency). IRS or IIRS is an iterative method with the convergence of the transformation matrix similar to that obtained by SEREP and yields generally a good approximation for the full model [14]. To achieve faster convergence, Xia et al. [15] modifies of the IIRS transformation matrix. A review and comparison between these model reduction methods was given in [13,16], and some applications can be found in [17,18]. Flodén et al. [19] compares the reduction effect of several reduction methods by using a structural model analysis. Generally speaking, the iterative methods can give better model approximation for the dynamic behavior of the original full model.

Modal-based reduction methods were developed based on the fact that displacement responses of structures can be expressed as a linear combination of the eigenvectors of the system [20,21], and involve various mode synthesis methods [22–25]. For mechanical engineering problems, most vibrations occur at relatively low frequency. Correspondingly, the eigenvectors corresponding to high frequency have little contribution to the responses. By truncating high-frequency modes and selecting a number of Ritz vectors (or modes) as projection space span, the high-order ODEs representing original full model in displacement space can be transformed into reduced ODEs expressed in modal or mode-displacement combined space. The second-order structure of the equations is retained.

State-space based reduction method is to find a smaller system with similar input–output behavior with the original large system, which has found its application in large electronic circuits and micro-electro-mechanical systems. The method includes singular value decomposition, Krylov subspace method and balanced truncation method. This reduction method requires the transformation of the second-order system into the first-order system. Such a transformation is not always convenient in some circumstances, structural vibration analysis, for example. It would be better to keep the second-order equations of motion of the structures. Then second order model reduction methods based on SVD, Krylov and balanced truncate method were developed [26–29]. The above-mentioned three categories of reduction methods have been used in different fields. Model and modal based methods are mostly used in the field of structural analysis, while the state-space based reduction method is mainly used in the field of system control.

It is known that vibration performance is crucial for vehicles. Model-based reduction methods will be used in this paper. Instead of being free, the models are either connected with other bodies, or some parts of the models are fixed or constrained in most circumstances. As a result of this, the vibration analysis usually needs to be performed for a same system with different boundary conditions. Since the reduction process is not a simple task, especially for the models with huge numbers of dofs, it is highly desirable that a free system reduction model needs only minor adjustments to adapt for various boundary conditions to form a constrained system. As the ODEs governing the reduction model have both similar second-order form and corresponding matrices with the original full model, it is common to assume that the boundary condition can be imposed directly to the reduction model derived from the free system.

The existing studies are mainly focused on the reduction process for particular ODEs (free or constrained systems for example), while the reduction model relationship between the free and constrained system is seldom concerned. The main objective of this paper is to study the approaches of handling the boundary condition for reduction models, and explore the possibility of easy transformation between free and constrained reduction models. Three commonly used boundary conditions, namely fixed boundary condition (FBC), prescribed motion (PSM) and coupling (COUP), are studied. For the sake of completion, the basic condensation scheme is firstly and briefly outlined in Section 2. The handling approaches of various boundary conditions for reduction models are derived in Section 3. Numerical examples are given in Section 4 to validate the schemes. Finally some useful conclusions are drawn in Section 5.