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Dual Craig-Bampton component mode synthesis method for model order reduction of nonclassically damped linear systems ☆

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ABSTRACT

The original dual Craig-Bampton method for reducing and successively coupling undamped substructured systems is extended to the case of arbitrary viscous damping.

The reduction is based on the equations of motion in state-space representation and uses complex free interface normal modes, residual flexibility modes, and state-space rigid body modes. To couple the substructures in state-space representation, a dual coupling procedure based on the interface forces between adjacent substructures is used, which is novel compared to other methods commonly applying primal coupling procedures in state-space representation.

The very good arbitrary viscous damping of the dual Craig-Bampton approach is demonstrated on a beam structure with localized dampers. The results are compared to a classical Craig-Bampton approach for damped systems showing the potential of the proposed method.

1. Introduction

The increasing performance of modern computers makes it possible to solve very large linear systems of millions of degrees of freedom (DOFs) very fast. Since the refinement of finite element models is increasing faster than the computing capabilities, dynamic substructuring techniques or component mode synthesis methods still remain an essential tool for analyzing dynamical systems in an efficient manner. Componentwise analysis and building reduced models of submodels of structures has important advantages over global methods where the entire structure is handled at once. The dynamic behavior of structures that are too large to be analyzed as a whole can be evaluated. For finite element models, dynamic substructuring provides fast solutions when the number of DOFs is so large that solutions cannot be found in a reasonable time for the global structure. Furthermore, building reduced models of submodels of a structure enables sharing models between design groups and also combining models from different project groups. Thereby, each group does not have to disclose the detailed model that was used for the design. Only a reduced model of the component, which was engineered by one group, has to be shared with the other design groups or companies. Significantly less memory storage has to be used if reduced models including only necessary information are saved and shared. Moreover, the reduction of the DOFs of substructures is also important for building reduced-order models for optimization and control. Controllers can typically be designed only for models up to a small number of DOFs. Most optimization procedures perform many iterations for certain parameters of a

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model, which is much faster and more efficient if reduced models can be used. If a single component of a system is changed or optimized, only that component needs to be reanalyzed/reoptimized and the entire assembled system can be analyzed at low additional cost. Thus, dynamic substructuring offers a very flexible approach to dynamic analysis [1–8].

Dynamic substructuring techniques reduce the size of large models. The large model is thereby divided into N substructures; each substructure is analyzed and reduced separately and then assembled into a low-order reduced model. This low-order reduced model approximates the original large model's behavior. During this process, each substructure's DOFs are commonly divided into internal DOFs (those not shared with any adjacent substructure) and boundary or interface DOFs (those shared with adjacent substructures and therefore forming the model's interface DOFs). Many substructuring methods that work with second-order equations of motion have been proposed in the past [1–3,5,9–11]. Only the substructures' mass and stiffness properties are commonly taken into account for the reduction. In doing so, the undamped equations of motion are assumed to correctly describe the substructure dynamics and it is assumed that there is no damping or that damping effects are completely negligible when building the reduction basis. Most substructuring methods work with the undamped equations of motion and afford great approximation accuracy if the underlying system is damped only slightly or not at all.

Dynamic substructuring techniques can be classified depending on the underlying modes that are used [4]. The term mode can refer to all kinds of structural shape vectors. The most popular approach is a fixed interface method, the Craig-Bampton method [1], which is based on fixed interface normal modes and interface constraint modes. The substructures are assembled using interface displacements, which is referred to as primal assembly. Many other methods, such as those of MacNeal [2], Rubin [3], and Craig-Chang [9], employ free interface modes, (residual) attachment modes, and rigid body modes and assemble the substructures in primal fashion as well. In contrast, the dual Craig-Bampton method [5] also employs free interface normal modes, (residual) attachment modes, and rigid body modes to build the substructures' reduction bases, but uses interface forces to assemble the substructures, which is referred to as dual assembly.

None of the aforementioned methods considers any damping effects when performing the reduction or, for simplification, proportional damping is assumed, which is the usual approach to damping [12]. If the damping properties are nonproportional (also called nonclassical) and damping significantly influences the dynamic behavior of the system under consideration, then the approximation accuracy of these methods can be very poor since the damping characteristics are represented inaccurately [13]. Hasselman [13] insisted that the assumption of a proportional damping model is inadequate to treat real systems [12]. There are many important instances in which these damping assumptions are not valid [14]. For example, structures with active control systems, with concentrated dampers or with rotational parts fall in this category [15]. Damping prediction, based on modal synthesis techniques utilizing only proportional damping information, is inappropriate [16]. This was demonstrated by Beliveau and Soucy [16] for the classical Craig-Bampton approach. Therefore, there is generally no justification to neglect damping properties for the computation of the reduction basis [13]. The fact that decoupling the damped equations of motion is not possible using classical modal analysis [17] will be highlighted in Section 2. One procedure to handle and decouple nonclassically damped systems is to transform the second-order differential equations into twice the number of first-order differential equations, resulting in state-space representation of the system, which was published by Frazer, Duncan and Collar [18] and made far clearer by Hurty and Rubinstein [19]. Solving the corresponding eigenvalue problem allows the damped equations of motion to be decoupled, but complex eigenmodes and eigenvalues will occur. Hasselman and Kaplan [20] presented a coupling procedure for damped systems, which is an extension of the Craig-Bampton method [1], which employs complex component modes. Beliveau and Soucy [16] proposed another version, which modifies the Craig-Bampton method to include damping by replacing the real fixed interface normal modes of the second-order system by the corresponding complex modes of the first-order system. Craig and Chung [14,15] and Howsman and Craig [21] study various first-order formulations leading to complex component modes. Craig and Ni proposed a procedure for the application of complex free interface normal modes [22]. Brechlin and Gaul gave methodological improvements for the numerical implementation of dynamic substructuring methods [23]. A report of de Kraker [24] gives another description of the Craig-Bampton method for damped systems using complex normal modes. De Kraker and van Campen also generalized the Rubin method for general state-space models [25].

The dual Craig-Bampton method [5] is fundamentally different from the other methods in that it assembles the substructures using interface forces (dual assembly) and enforces only weak interface compatibility. The reduced matrices associated to the dual Craig-Bampton method have a similar sparsity compared to the Craig-Bampton reduced matrices, but are less cumbersome (dense) than the reduced matrices obtained by other methods based on free interface modes [5]. Approximating eigenfrequencies, the dual Craig-Bampton method is outperforming the classical Craig-Bampton method using the same number of normal modes per substructure with comparable computational effort and having similar sparsity pattern for the reduced matrices [8]. The promising dual Craig-Bampton, which produces very good results for the approximation of undamped systems [5,6,8,26,27], has not yet been applied to damped systems. Therefore, we want to extend the dual Craig-Bampton method and demonstrate its potential for the case of nonclassically damped systems.

In this contribution, the original dual Craig-Bampton method for reducing and coupling undamped systems will be modified for general viscous damping. The final reduction is now based on the use of complex free interface normal modes, residual flexibility modes, and state-space rigid body modes. A dual coupling procedure based on the interface forces between adjacent substructures is used to couple substructures in state-space representation. This is novel compared to other methods, which commonly apply primal coupling procedures in state-space representation.

The traditional theory of decoupling by classical modal analysis is concisely surveyed in Section 2. The inadequacy of classical modal analysis for decoupling damped systems is also demonstrated. The terminology and notation used throughout