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Using singular value decomposition of component eigenmodes for interface reduction

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ABSTRACT

The aim of this paper is to describe the development of a reduced order model for modal analysis in a design context. The design process of most industrial systems is based on the re-utilization of certain components. Here, we propose a reduction method involving component eigenmodes to recover the modal behaviour of an assembled structure. The contribution of this work is that it uses component eigenmodes to build an interface reduction basis. Lastly, the reduction methodology proposed is compared to the Craig and Bampton method by applying it to two case studies of which one is an industrial model of an open rotor blade.

1. Introduction

The mechanical design of a system involves numerous investigations, including in particular the validation of its dynamical behaviour over its operating frequency range. This type of analysis can be performed numerically using the finite element method. However, in this context, the accuracy and level of detail required involve models whose significant sizes lead to time-consuming simulations. Moreover, the optimization process of such a system may demand a large number of validation computations that considerably slow down the design process. In this paper, the industrial case study considered is of modest size by current standards but subject to tens of redesign iterations. It is managed using a basic laptop.

Nowadays, reduction methods are used industrially to solve large and complex structural dynamics problems and reduce simulation time. Recent reviews of these methods were carried out in [1,2]. These methods allow evaluating the behaviour of models (sometimes in real-time [3]) incorporating several million degrees of freedom (DoF), see for example [4–6]. The dynamic substructuring technique (DS), first initiated by Hurty in the early 1960s, was of paramount importance in this progress. Indeed, the basic idea of this technique is to consider a large model as an assembly of smaller models that are easier to handle. Two main families can be identified [7] among these DS-based methods, namely Direct Coupling (DC) and Component Mode Synthesis (CMS). Whereas direct coupling deals with the enforcement of the Dirichlet and/or Neumann conditions on the contact interfaces in the nodal space, the CMS method imposes these conditions in the reduced space through the choice of the reduction vectors [8]. Indeed, CMS methods often consider the reduction of independent component finite element models whose interactions are described with modes.

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Nomenclature

$\mathbf{K}$, $\mathbf{M}$, $\mathbf{Z}$	stiffness matrix, mass matrix, dynamic stiffness matrix
$\boldsymbol{\Lambda}_k$	spectral matrix associated to structure k
$\mathbf{I}_n$	identity matrix of size $n \times n$
$\mathbf{u}$, $\mathbf{f}$	displacement, force vector
ω	circular frequency
$\star_i$	internal DoF of $\star$
$\star_b$	boundary DoF of $\star$
$\boldsymbol{\phi}_k$	free eigenmode of the structure Σ_k
$\boldsymbol{\psi}_k$	eigenmode of the structure Σ_k where the b DoF are fixed
$\star^\top$	transpose of $\star$
$\tilde{\star}$	reduced variable $\star$
n_k	number of DoF associated with the structure Σ_k
n_{ϕ_k}	number of vectors $\boldsymbol{\phi}_k$

The coupling condition associated with dynamic substructuring methods (primal, dual or hybrid) also has a significant impact on the performance of the reduced order model. Primal coupling focuses on maintaining conformity with the Dirichlet boundary conditions between the contacting components, to ensure the accurate description of the displacement fields of the structure assembled. The dual coupling formulation is based on the Neumann condition so that the coupling condition is weakly enforced.

The advantages provided by dynamic substructuring methods to structural dynamics are numerous [7]. They allow evaluating the behaviour of a structure that is too large or too complex to be analysed as a whole [4]. Indeed, the matrix inversion and eigensolution algorithm lead to quite considerable computational costs, thus the beneficial aspect of breaking down a large problem into a set of small ones is immediate. Moreover, as substructuring involves independent computations on the components, the parallelism achieved is widely used in classical methods such as the Craig and Bampton, MacNeal, FETI (Finite Element Tearing and Interconnecting) [6] and AMLS (Automated Multi-Level Solver) [9,10] methods, as well as in more recent methods [4].

Another feature provided by substructuring is that the contribution of each component to the overall response of the structure assembled is identified. This investigation can be achieved using the free eigenmodes of components as reduction vectors. From the design point of view, this type of analysis provides access to data that can be used to guide the redesign of components independently. Certain dual CMS methods using component free eigenmodes can be cited, such as the MacNeal method [11] and, more recently, the dual Craig and Bampton method developed by Rixen [12] and [13–15]. Nevertheless these methods are based on maintaining continuous force at the contact interface. Such an approach may not be well-adapted when the displacement field is of primary importance. It is noteworthy that hybrid methods mixing both primal and dual techniques can provide a good trade-off between the description of the force and displacement fields [16].

Another great advantage provided by dynamic substructuring is linked to its capacity to enrich the model assembled with experimental measurements and to combine them with other models. It is thus possible to evolve from an initial model as the product design progresses, i.e. using experimental data from fabricated parts of the assembly and increasing its level of detail by combining it with other substructures. In other words, the assembled model of a system can be progressively enriched by taking into account the contribution of an increasing number of components.

In the present work, we seek a good description of the displacement field, justifying the use of reduction methods based on primal coupling. Martinez et al. [17] showed that primal coupling can be conjugated with the use of component eigenmodes as reduction vectors. While using free-free eigenmodes allows describing component behaviours, improvement vectors are essential to accurately recover the kinematics of the system assembled. Thus the major difficulty of this approach is that of choosing the improvement vectors that will be easy to compute and which correctly represent the potential interface motions. Also, their number should not be linked to the size of the contact interface [18,19,4,20,14,21].

To sum up, the aim of this work is to propose a reduction methodology with the following requirements:

- The reduction should provide a compact reduced order model: this goal is achieved through interface reduction.
- The reduction method must be oriented towards the modal analysis of the system assembled.
- The method's accuracy must be acceptable. This will be verified by comparing it with the Craig & Bampton method.

This paper proposes a kinematic reduction methodology that relies on primal direct coupling (DC). The modal behaviour of the structure is recovered using a Ritz subspace spanned by component free eigenmodes and enrichment vectors. These enrichment vectors are obtained with different circular frequencies ω. Classically, reduction methods like the Craig and Bampton method are limited by interface size. The central idea of the present work is to reduce the interface using the component free-free eigenmodes. The interface modes are evaluated using the singular value decomposition (SVD) of the component eigenmode interface restriction. This approach allows building a reduced order model using component free eigenmodes whose size and accuracy can be tuned by selecting SVD-interface modes. Indeed, when looking for the N first natural modes, N different interface vectors are obtained at most by limiting the N natural modes at the interface. N does not depend on the number of interface DoFs; however, in Craig-like methods the reduction basis does. This is why the method proposed tries to retrieve these N different interface vectors, regardless of the quality of the interface mesh. Two radically