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Accelerating parametric studies in computational dynamics: Selective modal re-orthogonalization versus model order reduction methods

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ABSTRACT

In the dynamic analysis of a structure, it is frequent the use of parametric studies to consider several design configurations or possible modifications of the structure. These changes modify the physical properties of the structure, and therefore, finite element models need updates in order to compute the response of the modified structure. A wide variety of model order reduction methods which may be suitable for this task has been developed, either static or dynamic, which also consider non-classical damping, which is especially relevant in the design of vibration absorption devices. In this paper, we compare the use of selective reorthogonalization with other model order reduction techniques, both in terms of computational time and in accuracy, using three computer architectures. The proposed reorthogonalization method allows for parametric structural modifications and evaluates the solution using a modified complex modal domain only along a selection of a few degrees of freedom that are relevant for the dynamic analysis of the system. This acceleration method does not result in any significative decrease of the quality of the results of interest due to approximations, whereas remains very competitive when compared to usual model order reduction techniques.

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1. Introduction

In a typical engineering office, large structures require complex finite element models which may have hundreds of thousands of degrees of freedom [1]. These models are generated under some structural conditions, which may change during the design process or the life of the product. Therefore, the study of the dynamic response of a structure under loads or phenomena which vary over time imply, in many cases, the use of parametric analyses over very large finite element models, taking into consideration several design configurations or modifications of the structure. These changes modify the physical properties of the structure, and therefore, the finite element model to analyse the behaviour of that structure must be updated. A variety of case studies exemplify this circumstance: civil structures (buildings or bridges) under seismic loads, changes of loads in a structure, machinery, structural health monitoring to predict the variation of the dynamic behaviour after damages such as delaminations or impacts, a crack onset or growth, or even a blade loss event in an aircraft.

Possible modifications of the finite element models include, in practice, the addition of new small substructures, changes in the stiffness of some parts, added or eliminated mass, installation of damping devices, etc. All these modifications frequently require parametric studies in which the dynamic response of the updated structure, under some loading types, is analysed as a function of these parameters. These parametric studies are extremely expensive when performed over large structures, because they take important computer resources (CPU time and disk space) and block the expensive licenses of professional finite element programs.

The first step in the dynamic analysis of a structure is usually the computation of eigenvalues and eigenvectors [1]. Much effort has been taken in order to improve this task [1–4], resulting in a wide variety of very optimized and versatile methods. For a long time, a lot of work has also been invested into the development of diverse techniques for the reduction of the models, so that the costly analysis of complete, overdetailed models for the problem at hand, can be avoided. These techniques have been applied to local-global analyses, re-analyses, optimization, eigenvalue problems, vibrations, buckling, sensitivity studies of control parameters in

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design, and damage detection [5,6]. As the reduced model does not retain all the characteristics of the whole structure, the main objective of the reduction techniques is to achieve the greatest reduction of the model but with the minimum loss of information for the specific analysis.

A usual method to reduce the size of models is frequently developed through a coordinate transformation matrix which links the actual displacement coordinates of the complete structure with retained coordinates of the reduced model. If this mapping matrix is constant in time, velocities and accelerations follow the same relation and the method is frequently coined with the word static; otherwise referred to as dynamic.

The reduction techniques can be classified from the type of the variables employed in the reduced model: physical variables, generalized variables and hybrid. The first technique, which consists in retaining in the reduced model only some of the physical variables of the complete model, is the most obvious technique, does not loose the physical sense of the problem and is usually named condensation [5]. The part of the mapping matrix which links the reduced degrees of freedom (slave degrees of freedom) with those retained, is usually called condensation matrix. When this matrix is constant, ignoring the dynamic effects, it is called static condensation [7]. This method is adequate only for the low range of frequencies between zero and a cut-frequency which depends on the (master) retained degrees of freedom. Although this reduction is computationally more efficient than the other which involve non-physical variables, the precision and convergence obtained largely depend on a proper selection of the retained (master) degrees of freedom [8].

Among the dynamic condensation matrices, three different types can be distinguished: dependent on one eigenmode, dependent on some modes and dependent on the system response. In the first simplest case, the matrix is defined as the relation in a given eigenvector between the master degrees of freedom and the slave (not retained) degrees of freedom. Thus, using the equilibrium equation, the resulting transformation matrix depends on the eigenvalue associated to that mode. The accuracy for that mode is greatly improved, but not necessarily for the other modes. The condensation matrix which depends on more than one mode is the same as the one proposed in the so-called System Equivalent Reduction Expansion Process (SEREP) [9]. The condensation matrix which depends on the system response is more elaborate and is defined as a function of the relations between the responses in the slave and master degrees of freedom, obtained using a temporal integration scheme. The non-physical coordinates are usually named generalized coordinates. Two methods which use these coordinates are the modal coordinates method and the method which uses the more general Ritz bases [1–3,10].

In the modal analysis method, the dynamic response is expressed as a function of the modal coordinates in the modal space (with the same dimension as the physical space), but the solution is usually approximated considering only part of the modal coordinates [11]. Depending on the excitation frequency, the considered or retained modes are those nearest to zero hertz or those inside an interest frequency range, being this selection related to the loss of precision in the computed dynamic response. In presence of damping, the decoupling of the system of equations is possible only under certain circumstances [12–14].

The use of Ritz vectors as generalized coordinates can approximate with good agreement the dynamic behaviour of the structure if the loads are known. The Ritz vector construction, is computationally more efficient than obtaining the exact eigenvectors, but the resulting equilibrium equation has coupled components because it is a non-orthogonal coordinate's transformation. The method is advantageous when a limited number of eigenvalues is required in large models and it is also used for accelerating the iteration process in the search of eigenvalues, as proposed by Bathe in his subspace iteration method [1]. The static correction method, the modal acceleration method [15] and the modal truncation augmentation [16,17] improve the solution with correction terms. In these space decomposition methods, the key is the calculation of the eigenvalues and eigenvectors, with high computational costs in large structures [18–25].

The hybrid reduction can be considered as a combination of the static condensation applied to the non-retained degrees of freedom and the reduction in the modal space applied to the retained degrees of freedom [26]. These methods are close to the Component Modal Synthesis (CMS), which can be classified into three variants: fixed interface (Craig-Bampton method) [27,28], free interface, and hybrid, being the last one a combination of the two previous methods. This method divides the structure into components and obtains the matrices of the system for each component under some interface hypotheses, which are later assembled resulting in a reduced global model which is solved in a space of generalized coordinates. The variant which consider the interface degrees of freedom free in the space has the advantage of avoiding the presence of these degrees of freedom in the final movement equations, though the convergence is reduced [29,30].

All the reduction techniques are generally applied in one unique step. However, several iterative algorithms have been developed seeking for an improvement in the precision of the solution [31–33] or to solve the corresponding non-linearity of the resulting equations [34,35].

There are many other reduction techniques available in the literature which we will not address below because they are not arguably so fitted to our purpose of analysing local changes. Some of the most relevant ones are the Balanced Realization Method [36] based on control techniques, the Proper Orthogonal Decomposition (POD) which uses the singular values of the matrices of the system instead of the eigenvalues [37,38], the Proper Generalized Decomposition (PGD) [39–41], or the Condensation Model Reduction (CMR) which reduces the model through a second order differential operator [42].

In this paper we select some of the described methods which allow for general non-proportional damping and formulate them in a similar framework in order to compare them with the proposed acceleration method based on a selective reorthogonalization (MADAM: Method for Accelerating Dynamic Analyses under Modifications) [43]. Whereas MADAM has been recently developed for accelerating parametric analyses in local modifications relevant in many applications [44–47], it is an open question if it is competitive against condensation methods in accelerating general dynamic analysis. The answer to this question is relevant, for example, for further nonlinear applications in earthquake engineering, where local plastic dissipation (from plastic hinges or from specially designed plastic dissipation devices) and modal changes are common during the earthquake. Because MADAM may retain the information of all modes at the relevant locations through frequencies and modal components, it entails no approximation unless modal truncation is employed [48–51]. The application of MADAM in these cases is rather straightforward, whereas the application of the condensation methods would entail frequent updates of the transformation matrices. A main asset of the MADAM method is that it can be easily implemented in any engineering office to account for those nonlinearities (in Python, MATLAB, Octave, Fortran) using standard output (modes and frequencies) of commercial finite element codes to small files, liberating computational resources and the professional licenses of the finite element codes for other uses.

The rest of the manuscript is structured as follows. We first briefly review the selected model order reduction methods under a common framework for comparison with the proposed method,

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