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Adaptive parametric model order reduction technique for optimization of vibro-acoustic models: Application to hearing aid design ☆

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ABSTRACT

Finite Element (FE) models of complex structural-acoustic coupled systems can require a large number of degrees of freedom in order to capture their physical behaviour. This is the case in the hearing aid field, where acoustic-mechanical feedback paths are a key factor in the overall system performance and modelling them accurately requires a precise description of the strong interaction between the light-weight parts and the internal and surrounding air over a wide frequency range. Parametric optimization of the FE model can be used to reduce the vibroacoustic feedback in a device during the design phase; however, it requires solving the model iteratively for multiple frequencies at different parameter values, which becomes highly time consuming when the system is large. Parametric Model Order Reduction (pMOR) techniques aim at reducing the computational cost associated with each analysis by projecting the full system into a reduced space. A drawback of most of the existing techniques is that the vector basis of the reduced space is built at an offline phase where the full system must be solved for a large sample of parameter values, which can also become highly time consuming. In this work, we present an adaptive pMOR technique where the construction of the projection basis is embedded in the optimization process and requires fewer full system analyses, while the accuracy of the reduced system is monitored by a cheap error indicator. The performance of the proposed method is evaluated for a 4-parameter optimization of a frequency response for a hearing aid model, evaluated at 300 frequencies, where the objective function evaluations become more than one order of magnitude faster than for the full system.

1. Introduction

Simulation is gaining relevance in industrial design procedures, which have evolved from a purely prototyping and testing approach to a context where numerical simulation is used from the early phases. Obtaining reliable models is a key point in the

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design process, and as more and more accuracy is required, the complexity of the models increases. In the field of hearing aids, numerical vibro-acoustic analysis is essential for the study of problems such as feedback; currently the main gain limiting factor of the hearing devices. The high number of small parts that conform them, the strong structure-acoustic interaction between those parts and the internal air volume require models with a large number of Degrees Of Freedom (DOFs) in order to capture the physical behaviour accurately. Therefore, significant computational challenges are encountered when solving problems that require iterative and/or repeated solutions of the numerical model. Tasks such as uncertainty analysis by means of Monte-Carlo methods, or parametric and topology optimization, require solving the system of model equations repeatedly for a large number of variations of different parameters. Therefore, the time required for solving the numerical problem at each iteration becomes a critical factor. In the present work, we develop an adaptive model order reduction technique and apply it to a hearing aid design problem.

In a recent paper [1], topology optimization of a part of a hearing instrument including structure-acoustic interaction was performed. Optimizing one part of the device requires the complete assembly to be taken into account when there is a strong acoustic-mechanical interaction, since the multiple vibrational and acoustic transmission paths between parts have a significant influence on the system performance. To facilitate the study, the performance was evaluated and optimized for a limited number of frequencies; therefore, the effects at the rest of the frequency range were not controlled. This highlights the need to develop computational reduction techniques that allow optimization to be carried out with a higher level of accuracy and frequency resolution.

Model order reduction techniques have been described in the literature and applied in several fields [2–4]. The earliest research on the topic deals with structural dynamics problems, with the Component Mode Synthesis (CMS) method being developed in the 1960s [5,6]. When modal-based methods were to be extended to problems with structure-acoustic interaction, different approaches were developed to construct the reduction basis. Since solving the coupled eigenvalue problem requires higher computational effort due to the asymmetric nature of the matrices when the pressure-displacement formulation is used, one suggested approach [7] consisted in using the uncoupled structural and acoustic modes, which is an efficient solution for problems with a weak structure-acoustic coupling. However, for problems with strong interaction, a large amount of modes are required in order to obtain an accurate reduced model [8], making it a poorly efficient technique. With the recent improvements on eigenvalue solvers and computational power, solving the asymmetric problem has become less challenging; therefore, the coupled modal vectors, that better describe true behaviour of the system, can now be used in practice. Another issue that arises from the asymmetry of the matrices is that the modal vectors do not form an orthogonal basis, which has been addressed in the literature in two ways: by using both left and right eigenvectors [9,10], or by applying orthogonalization techniques on the right eigenvectors [11]. The two approaches have been compared by the authors in Ref. [12], which showed that the second approach is more suited to the present problem, and is therefore employed in this work.

In CMS, the model is divided in substructures, which are reduced internally while the interface DOFs are kept unmodified. Even though interface reduction methods have been developed [13,14], this method is most efficient for systems that can be divided at low-dimensional interfaces, such as the pipes studied in Ref. [11], but it can be difficult to efficiently substructure systems that consist of complex 3D parts, as in hearing aid models. Despite the cost of solving the full eigenvalue problem, it turns out that a more efficient technique [15] consists in reducing the complete structure in terms of the global modal vectors, since fine resolution frequency response calculations can then be done at a very low computational cost on the reduced system. Therefore, this approach is selected in our work.

For parametric optimization purposes, a new modal reduction basis would have to be calculated for each variation of the parameter values when using the suggested approach (unless the modal vectors are not sensitive to the parameters, as assumed in Refs. [16,17]). This would still be faster than calculating the full system frequency response if the number of considered frequencies is large; however, parametric Model Order Reduction (pMOR) techniques have been developed to make this process even more efficient. The Multi-Model Reduction (MMR) technique is one of the most straight-forward pMOR methods, which consists in constructing a global reduction basis that is valid for any value of the parameters within a given design domain by concatenating the modal vectors calculated at several points in the parameter space in a global reduction matrix [4,18]. The number of included points should be sufficient to ensure that the reduction error at any point in the domain is below a required level. The resulting global vector matrix is then orthogonalized, since some modal vectors calculated at different sampled points can be linearly dependent, and they would otherwise result in ill-conditioning. When using MMR for coupled problems, the fact that the modal vectors resulting from the asymmetric matrix system are inherently not orthogonal should also be taken into account.

The MMR technique is usually applied in an offline-online fashion, where the reduction basis is constructed first (offline) and used for very fast function evaluation during the optimization (online). A drawback of this approach is that the offline phase can become very costly for an increasing number of parameters, since (a) the full model eigenvalue problem must be solved for each point that is included in the basis, and (b) the full model solution must be calculated at a representative sample of non-included points to evaluate the reduction error and ensure accuracy. To avoid problem (b), error bounds or error estimators that are cheaper to compute can be used instead of the true error [19]. Tight error bounds can be found for specific types of partial differential equations [20]; however, we will use a residual-based error indicator in this work, since they can be applied for any kind of problem and have already been successfully used in frequency response calculation problems [21].