Efficient simulation of vibro-acoustic problems with poro-elastic damping using a Matrix-free Model Order Reduction scheme

Stijn Jonckheere[abc], Onur Atak[b], Hadrien Bériot[b], and Wim Desmet[a,c]

[a] *KU Leuven, Department of Mechanical Engineering, Division PMA,*
Celestijnenlaan 300 - box 2420, B-3001 Leuven, Belgium.
[b] *Siemens Industry Software NV, Digital Factory, Product Lifecycle Management - Simulation and Test Solutions,*
Interleuvenlaan 68, B-3001 Leuven, Belgium
[c] *Member of Flanders Make. (first.last,first.last)@e-mail.com*

stijn.jonckheere@kuleuven.be

Introduction

Instigated by customer expectations and ever tightening regulations on noise emissions, the vibro-acoustic performance of products has become a key design feature. The fact that many products nowadays use various lightweight materials makes that it is often difficult to meet all these requirements. To ensure this, damping treatments – often multi-layered – are added, but almost always a posteriori.

Predicting multi-layers in efficient simulations is essential in a modern design environment. These frequency dependent damping materials typically operate on a dynamic decoupling in order to dissipate energy more efficiently in the near-field. These effects make that the mesh should be sufficiently refined to capture the short wavelengths and high gradients. In order to alleviate long computation times, a variety of model order reduction (MOR) techniques have been developed. Typically, they can be divided into three groups, being modal-, Krylov- and truncation-based methods.

Many of the available MOR techniques, however, still struggle when material properties are complex and especially when they have strong frequency dependency. Some attempts in the field of poro-elastic materials were made, especially for modal reduction techniques. For a more complete overview of reduction methods for poro-elastic materials, the reader is referred to [1].

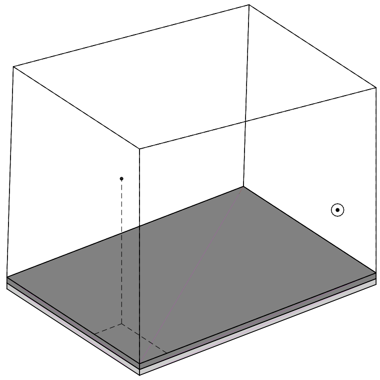
However, all of these procedures are quite intrusive into the system matrices, which hampers general applicability and makes each of the methods dependent on the chosen method (e.g. Finite Element Method), the formulation for the poro-elastic problem (e.g. equivalent fluid, u-U, u-p, u-w, etc.) and the other physics involved (e.g. coupling to acoustics or structural vibrations). This contribution proposes a Krylov-based method [2] which does not require knowledge on the underlying mathematical model, and can hence be considered “matrix-free”. This black box approach holds for both undamped and damped cases and can robustly cope with complex frequency dependency of the parameters.

Matrix-Free rational Krylov interpolation

The Matrix-free rational Krylov method [3,4] is a Krylov-type MOR technique. As such it uses forced responses of the system to span a projection subspace which is used to project the full order model (FOM) on. Contrarily to conventional Krylov approaches, the method does not require any detailed knowledge of the underlying model equations; the reduced order model (ROM) is built up using the explicit transfer functions.

The quality of the ROM greatly depends on the number and placement of the interpolation frequencies. An adaptive procedure is proposed in this work, where the quality of the ROM can be improved iteratively by including information where the approximation error is the largest. As a cheap error criterion, the relative error between two subsequent ROM’s is used. This is complemented with a masking procedure that prevents overinvestment of FOM evaluations at locations where the ROM has just been enriched. This way, the algorithm is encouraged to select frequencies all along the considered frequency range, yet still more at the location where they really matter. The iterative refinement is stopped when the relative error between two subsequent ROM's has reached a set tolerance value. To prevent premature termination of the algorithm, a second convergence criterion is used in the form of a relative error between the new frequency evaluations of the FOM and the prediction using the previous ROM.

Numerical application



As a numerical application, a convex acoustic cavity (1.122m x 0.82m x 0.982 m) is used. The walls of the acoustic cavity are considered rigid and the cavity is excited by an acoustic volume source with an amplitude of q = 1 m³/s, located in the point (1.03 ; 0.12 ; 0.3). The air inside the cavity is in contact with a poro-elastic multilayer placed at the bottom. The multilayer consists of two open-pore poro-elastic layers of 0.025 m. The bottom material is a carpet material [5] and the top material is a polyurethane foam [6]. The layers are glued at the interface. Sliding edge conditions are applied to the boundaries in contact with the cavity walls.

The acoustic pressure response in the point (0.13 ; 0.28 ; 0.68) is simulated over a frequency band from 50 to 800 Hz using the Finite Element Method and using the (u,p)-formulation of Biot's equations. The FOM contains 273741 nodal DOFs.

Using the Matrix-Free method, a ROM is constructed of 42 reduced DOFs which required 84 FOM evaluations. As Fig. 1 shows, the ROM is able to predict the reference solution within a tolerance of 1%. As earlier research [4] indicated the Matrix-free overhead is negligible, the speed-up can be directly calculated from the ratio of FOM evaluations as 10x. Moreover, as damping increases, this speed-up is even more pronounced [4]. For the same computational cost, the ROM can produce results up to two orders more accurate than the FOM which is calculated by using the same number of evaluations but with linear spacing between the evaluation points.

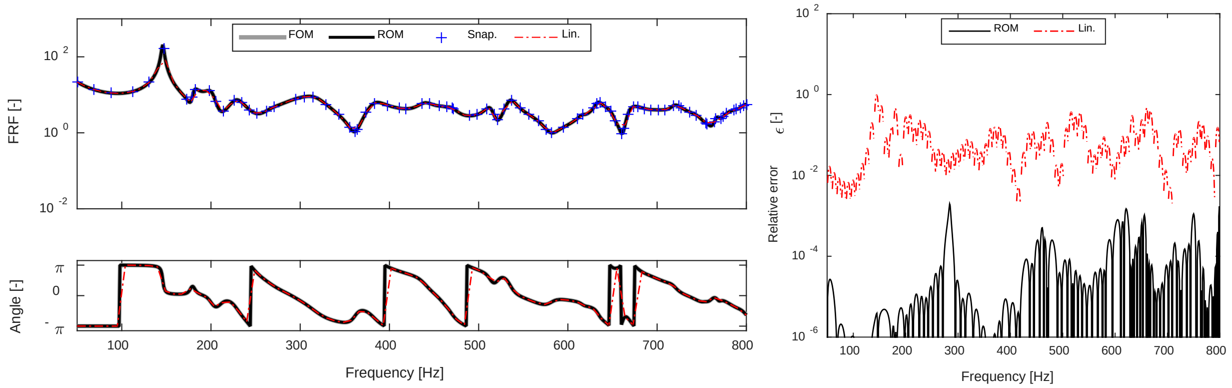


Figure 1: MatrixFree ROM prediction accuracy compared to FOM and FOM sampling with similar computational cost

Acknowledgements

The European Commission is gratefully acknowledged for their support of the DEMETRA research project (GA 324336). The authors gratefully acknowledge SIM (Strategic Initiative Materials in Flanders) and VLAIO (Flanders Innovation & Entrepreneurship) for their support of the ICON project M3NVH, which is part of the research program MacroModelMat (M3). The authors would also like to gratefully acknowledge the Research Fund KU Leuven.

References

[1] E. Deckers, S. Jonckheere, D. Vandepitte, and W. Desmet. Modelling techniques for vibro-acoustic dynamics of poroelastic materials. Archives of Computational Methods in Engineering, 22(2):183–236, 2015.
[2] E. Grimme, Krylov projection methods for model reduction, University of Illinois at Urbana-Champaign PhD thesis, 1997.
[3] X. Li, Power flow prediction in vibrating systems via model reduction, Boston University, College of Engineering, Boston, 2004.
[4] S. Jonckheere, X. Li, W. Desmet, A matrix-free Model Order Reduction scheme for vibro-acoustic problems with complex damping treatments, Proceedings of the 27th conference on Noise and Vibration Engineering (ISMA2016), Leuven (Belgium), 2016.
[5] P. Debergue, R. Panneton, and N. Atalla. Boundary conditions for the weak formulation of the mixed (u,p) poroelasticity problem. The Journal of the Acoustical Society of America, 106(5):2383–2390, 1999.
[6] T.E. Vigran, L. Kelders, W. Lauriks, P. Leclaire, and T.F. Johansen. Prediction and measurements of the influence of boundary conditions in a standing wave tube. Acta Acustica United with Acustica, 83(3):419–423, 1997.