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REDUCED-ORDER MODELING AND COUPLED MULTI-ENERGY DOMAIN SIMULATION OF DAMPED HIGHLY PERFORATED MICROSTRUCTURES

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ABSTRACT

Transient finite element simulations of electromechanical devices with highly perforated deformable or movable structural components are computationally very expensive or even prohibitive, when multiple energy domains and their mutual interactions have to be considered. This is in particular the case, when fluid-structure interactions have to be included in the physical models in order to analyze fluidic damping effects as they occur in microdevices with complex geometry. Especially perforations increase the computational expense drastically, because they require a highly resolved mesh with a large number of discretization nodes to obtain an accurate description of the damping behavior.

We developed a modeling toolbox in MATLAB that, starting from discretized FEM device models, enables the automated generation of physically-based mixed-level reduced-order models (Fig. 1); these constitute the proper basis for the coupled-domain simulation of complex microstructured devices within acceptable computation time. The underlying theoretical framework is provided by the generalized Kirchhoffian network theory. In this approach, a microsystem is decomposed into functional blocks, which are represented by reduced-order macromodels. Since these are based on a physical description of the functional behavior, they are scalable with design parameters and, after calibration, are predictive. A fast, but yet accurate system-level model of the full microdevice is obtained by interlinking them to form a generalized Kirchhoffian network, which inherently governs the exchange of energy and other physical quantities between the blocks. Thus, our methodology provides a natural and efficient way to tackle all the couplings between the electrostatic, fluidic, and mechanical energy domain. For the implementation of fluidic damping, we employ the Reynolds equation, which is discretized in form of a finite fluidic network and augmented by dedicated compact models to properly include the effects of perforations, edges and corners of the microstructure (Fig. 3). We obtain simulation results, which are in excellent agreement with the experimental findings [1,2].

A further enhancement of our method is achieved by employing the “reduced hole array” (RHA) scheme. This is an order reduction technique which groups a number of parallel compact models of perforations in arrays and replaces them with computationally less expensive ‘superhole’ compact models (Fig. 4). The RHA scheme has been implemented in our toolbox as an automated node condensation process steered by structural data that is extracted from the geometry of the microstructure. As illustrative example, we considered a deformable membrane with a total number of 1225 perforations (Fig. 2) and generated full and RHA macromodels with arrays spanning 4, 25 and 100 perforations. The VHDL-AMS models using RHAs show no significant loss of accuracy (Fig. 5), but lead to a drastic speed-up of computation time by a factor of 40 for the simulated response of the membrane to a voltage step (Fig. 6). Thus, by the integration of the RHA technique we are equipped with a powerful modeling toolbox to generate macromodels for a class of microstructures which is very difficult or even impossible to treat with finite elements.

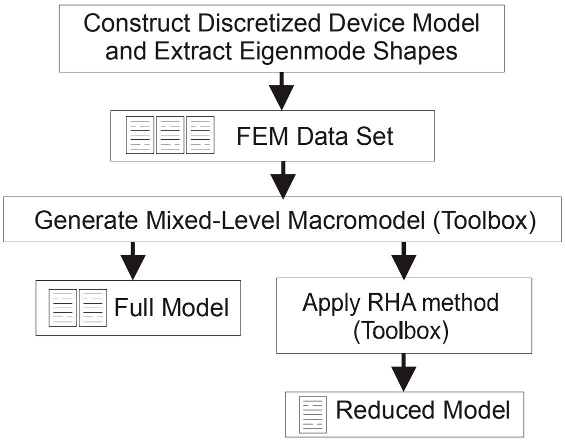

Fig. 1 Workflow of the automated macromodel generation using the MATLAB toolbox. The RHA process is implemented as an extension.

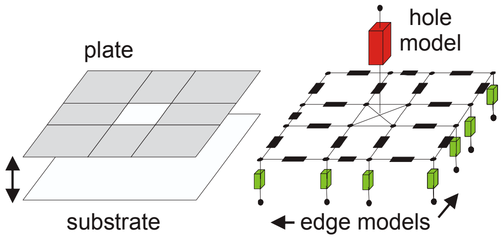

Fig. 3 Perforated plate and corresponding fluidic FN. Black blocks symbolize the discretized Reynolds equation; green and red blocks denote resistances accounting for edges and holes.

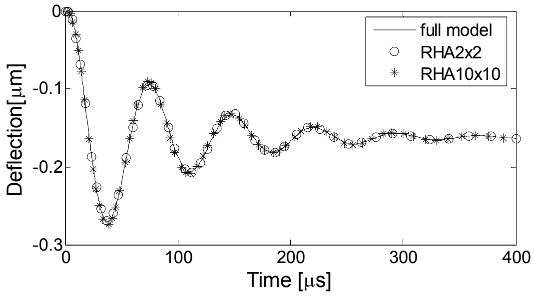

Fig. 5 Displacement of the membrane as response to a voltage step, calculated with the full model and different RHA models. No significant loss of accuracy is observed.

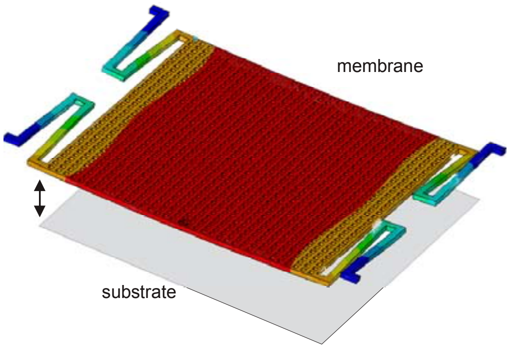

Fig. 2 Microstructured membrane perforated with 1225 holes. The membrane is electrostatically actuated. As the ambient pressure is 1013 hPa, the motion of the membrane is heavily affected by squeeze film damping in the gap to the substrate.

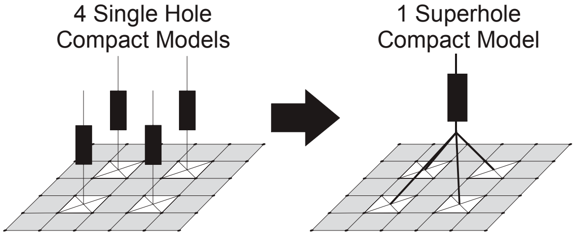

Fig. 4 Principle of the RHA technique: arrays of single holes are replaced by one 'superhole' compact model.

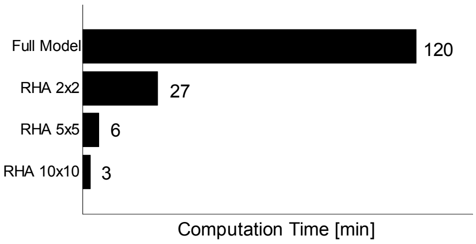

Fig. 6 Computation times of the full model and RHA models on a 3GHz processor. In this case, the computation time can be reduced by a factor of 40.

REFERENCES

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