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Homogenization of piezoelectric porous structures for peristalsis-driven flows

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Abstract

We present a homogenized model of a piezo-poroelastic material which enables to transport fluid against small pressure slope. To explore functionality of such metamaterial structures, we develop multiscale computational tools. The computational models arise from the homogenization of the fluid-structure interaction problem. Cell problems (at the microlevel) are obtained which provide characteristic responses of the microstructures with respect to macroscopic strains, fluid pressure and electric potentials. Although the deformations are assumed to be small, the macroscopic nonlinearity of the device is captured using the first order expansions of the homogenized coefficients with respect to macroscopic variables. As an optional feature of the smart devices, distributed valves are involved which strongly influence the macroscopic permeability of the material. For this, homogenized model of the contact problem was developed. We present examples of microstructures and results of the simulations as the proof of concept aimed at designing smeared peristaltic pumps in a bulk medium.

Keywords: piezo-poroelasticity, peristalsis, unilateral contact, homogenization, fluid saturated porous media, finite element method.

1 Introduction

Fluid transport in porous materials can be assisted by a controlled deformation of pores in time to produce a peristaltic effect; this principle is well known in biological tissues. The deformation of the porous skeleton can be driven by various phenomena involving other physical fields, such as temperature, or electromagnetic field. We consider piezoelectric (PZ) actuators connected to electrode circuits, both being distributed in an elastic skeleton, so that periodic, or locally periodic structures are created. To explore functionality of such metamaterial structures, we develop computational tools based on the multiscale homogenization approach. The computational models arise from the homogenization of the fluid-structure interaction problem, taking into account nonlinear effects, such as unilateral self-contact at the pore level, or deformation-dependent effective material parameters, such as hydraulic permeability, or other poroelastic coefficients. We present examples of microstructures and results of the simulations as the proof of concept aimed at designing smeared peristaltic pumps in a bulk medium. The computational tools are intended for subsequent two-scale design optimization of local microstructures according to objectives of the macroscopic functionality.

2 Methods

The homogenization procedure is based on the periodic unfolding method and the method of the oscillating test functions. In this way, local cell problems are obtained which provide characteristic responses of the microstructures with respect to macroscopic strains, fluid pressure and electric potentials. We rely on the model of a homogenized piezo-poroelastic medium obtained in paper [2], which allows for introducing local control of the distributed PZ actuators by the electric potential. This model is extended to describe viscous flows in deforming porous structures. To capture the peristaltic effects, nonlinear phenomena related to deformation are considered in an approximate way to keep the computational modelling effective as much as possible. For this, a linearization procedure is applied, being based on the sensitivity analysis of the local characteristic responses with respect to the macroscopic strains and pressures which modify the deformed configurations of the representative volume elements at the micro-level. In this way, by virtue of the methodology introduced in [1], we get first-order expansions of all the homogenized coefficients. As another strong nonlinearity related to deforming micro-pores, the unilateral contact at the pore level is considered. Under some assumptions concerning the pore geometry, a homogenized model is derived. For numerical solutions of the finite-element discretized two-scale problem, a consistent stiffness matrices of the macroscopic elasticity problem are derived. At the local level, the contact problem attains the form of a nonsmooth equation which is solved using the non-smooth, or semi-smooth Newton methods, as proposed in [4]. The evolutionary macroscopic model is discretized in space by the finite element method, while the implicit finite difference scheme is employed for the time integration.

3 Results

A model of the homogenized periodic fluid saturated piezo-poroelastic structures is obtained which captures nonlinear effects related to the deformation. The peristaltic flow in the porous structure is described by a nonlinear Darcy law with hydraulic permeability reflecting the deformed configuration of the local microstructure. For the derived incremental formulation of the two-scale poroelastic model with the unilateral contact interaction at the pore level a numerical implementation was realized using the in-house developed SfePy finite element code [5]. The numerical results illustrate some specific properties of the considered active porous structures. Influence of the following phenomena on the fluid propulsion efficiency of the generated peristalsis has been explored: actuation wave type, speed of actuation with respect to the peristaltic wave propagation, the scale effect.

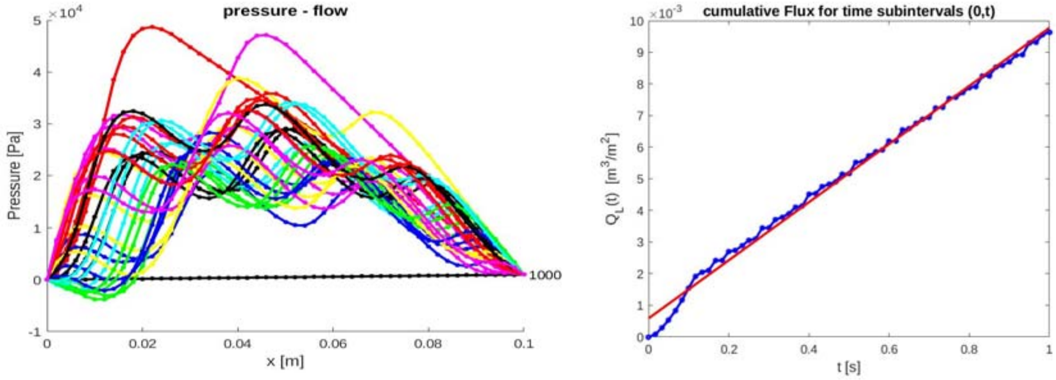

Figure 1: Generated pressure waves in a 1D specimen (left) and flow against the over-pressure (right).

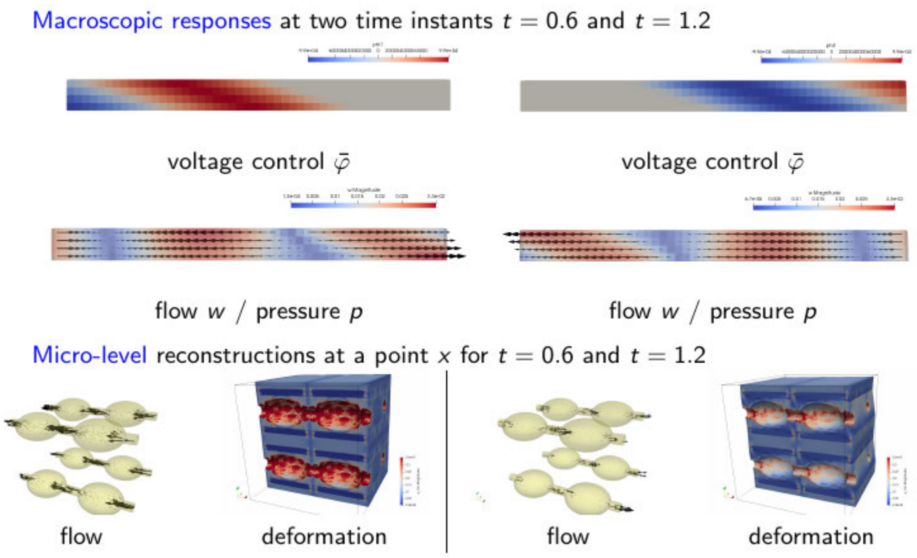

Figure 2: Illustration of the flow generated by the piezo-poroelastic smart material. Two scale simulations using the homogenized model.

4 Conclusions and Contributions

The presented work is a new contribution in the homogenization-based modelling of fluid-saturated piezo-porous periodic structures. The main purpose is to explore possibilities of transporting the fluid in such a porous medium. For the the fluid propulsion and also to control the flow direction in 2D, or 3D structures, the electrostatic field is employed. For a suitable excitation attaining the form of a propagating voltage wave, the pumping effect has been observed which drives the fluid against the pressure slope even if the structure deformation does not collapses the pore cross-sections. The proposed modelling approach combining advantages of the homogenization and the shape sensitivity analysis to linearize deformation-dependent properties provides an efficient numerical simulation tool. The self-contact modelling option has been tested on examples involving 2D structures which cannot describe realistic geometries because of the topology deficiency. Optimal design of 3D structures with a desired pumping efficiency presents a challenge in the virtual prototyping such smart structures [3].

Acknowledgements

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