

TOPOLOGY OPTIMIZATION OF ACTUATABLE POROUS LATTICES FOR PROGRAMMABLE PERMEABILITY

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Abstract

Actuable porous lattices are architected solids whose macroscopic effective properties can be changed on demand by external stimuli. By tailoring geometry at the unit cell level, these lattices can adapt stiffness, shape, and transport behavior rather than remaining fixed after fabrication. This adaptability is particularly attractive in applications where operating conditions vary over time, such as tunable filters, drug-delivery membranes, heat-exchange systems, and hydroponic cultivation substrates.

The optimal design of lattices typically relies on the identification of an optimized reference unit cell. In this context, inverse homogenization and topology optimization offer a route to automatically discover the unit cell layout that meets prescribed targets. However, designing actuable porous lattices introduces several challenges beyond standard structural and material optimization. Indeed, the optimization problem simultaneously considers two configurations of the unit cell, namely, the reference and the deformed (actuated) one. As a result, the numerical solution of such an optimization problem can require iterative remeshing of the actuated domain, which is costly and non-robust, and may complicate sensitivity analysis.

In this presentation, we focus on actuable lattices with programmable permeability, enabling the optimized system to open, close, or redirect flow pathways through controlled deformations. To this end, we propose a framework that couples mechanics and Stokes flow at the unit cell level, avoids repeated mesh updates, and enforces fabrication-relevant length scales with a view to the production phase. In particular, we formulate a density-based inverse-homogenization topology optimization problem in which a single material density field simultaneously controls elastic actuation and Stokes flow in the periodic unit cell, accounting for both the reference and actuated configurations. The Stokes cell problems are pulled back from the actuated to the reference unit cell by transforming the weak form of the equations via the deformation map, thus allowing

us to consider only the reference domain and avoiding the need for remeshing. The sensitivity analysis is then performed by setting up a nested adjoint system across the coupled elastic and fluid subproblems. The overall formulation is embedded in a robust density-based topology optimization framework with Helmholtz-based filtering and smooth projection to control minimum feature size and promote manufacturable designs.

The effectiveness of the proposed approach is assessed on 2D and 3D tests, considering thermal actuation, targeting either a decrease or an increase in selected components of the effective permeability tensor. In 2D, the examples exploit thermal expansion to either constrict dominant flow channels or reconfigure compliant features, yielding a controlled decrease or increase in permeability after actuation. In 3D, the method identifies microstructures that achieve stronger flow modulation, thus illustrating richer actuation mechanisms unavailable in planar settings.