Computational Design for Micro-Fluidic Devices using a Tightly Coupled Lattice Boltzmann and Level Set-Based Optimization Algorithm

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Recently the study of micro-fluidic devices has gained much interest in various fields from biological to engineering. The reason for this increased interest can be attributed to the technological progress in machining, allowing complex geometries to be manufactured, and the need for miniaturized devices in combustion and chemical analysis. These devices are concerned with low Reynolds number flows, resulting in a laminar flow regime, having dimensions that range from millimeters to micrometers. Although micro-fluidic devices can be implemented for mixing of multiple fluid species; this work is particularly interested in the mixing of two non-reacting iso-thermal and incompressible fluids. Therefore, whilst diffusivity dictates the mixing in low Reynolds number flows, in this case the mixing is governed only by turbulence. Thus, the mixing can be enhanced by using active or passive devices, such as moving parts or multi-holed baffle plates. In this study passive devices are considered, due to their ease of integration and stable operation, compared with active devices, which require an energy input in order to mix the flows. Complex geometries are required due to the presence of components in the direction of the flow which stretch and fold the fluid over the cross-section of the channel enhancing the turbulence of the system. Hence, areas of high stress are present due to the geometrical non-linearity of the micro-fluidic devices and high pressure ratios. This article develops a novel framework for a topology optimization algorithm that is coupled directly to the Lattice Boltzmann method, used for simulating the flow in the micro-fluidic device, for the objective of minimum compliance. This study focuses on the effect of the fluid-structural interactions by comparing the optimization results obtained by a fully coupled, where the loads are updated directly by the change in topology, and uncoupled, no update in the load, solutions on the design of micro-fluidic devices. The final compliance for both cases are compared and a trade-off is made between minimum compliance and computation time.

I. Computational Methodology

The numerical framework, which couples the topology optimization algorithm with the Lattice Boltzmann flow solver, is shown in Figure 1. The problem is defined, setting the initial topology and boundary conditions for the test case. The geometry is passed onto the flow solver, which outputs the pressures, and ultimately the forces, being applied to the topology. The current topology and loads are passed onto the Finite Element Method (FEM) module, which defines the structural boundary conditions and outputs the compliance of the structure. This is passed onto the topology optimization algorithm which calculates the sensitivities and updates the topology of the structure for the next iteration.

The numerical framework (Fig. 1) consists of two loops. The first is between the topology optimization algorithm and the FEM module, which is performed at every iteration. The second loop passes the updated topology back into the LBM flow solver. Due to the computational penalty of the LBM solver, the second loop is performed only after every n_{LBM} iterations. This is a predefined parameter, which ensures the topology has

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changed significantly, such that the loads are required to be updated. A trade-off between reduction in compliance and computation time is given in the results.

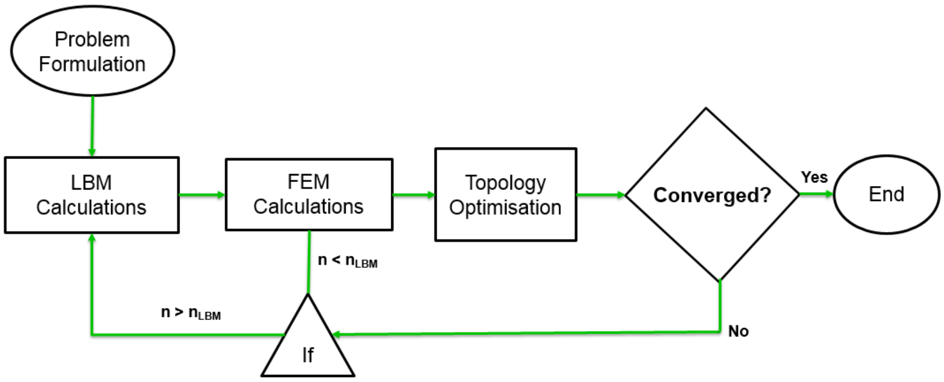

Figure 1. Numerical Framework for Coupled LBM-Topology Optimization.

II. Preliminary Results

In this section the preliminary results of the numerical framework are presented, along with a discussion and summary of the findings of this study. The preliminary results for the uncoupled and coupled algorithm are given.

First, the problem with no feedback to the fluid solver is analyzed. Therefore, the LBM is only performed once on the initial structure to obtain the pressure loads, which remain unchanged throughout the optimization. This represents the simplest and hence most computationally efficient case. Next, the coupled solution is presented, using a $n_{LBM} = 10$, with all other parameters identical to the uncoupled solution.

The initial and final topology for the uncoupled and coupled problem is shown in Figure 2.

Figure 2. Initial Topology (left) Final Topology Uncoupled (middle) Final Topology Coupled (right).

The final topology shows a much more complex structure (Figure 2), creating load paths to increase the stiffness of the baffle. All six holes from the original structure have been maintained; however, the topology of the holes differ significantly. Further, four smaller holes have been added to the baffle. Likewise, The final topology for the coupled case (Figure 2 (right)) differs significantly compared to the uncoupled solution (Figure 2 (middle)). Namely, the coupled solution has added two larger holes along the mid horizontal plane, which are not present in the uncoupled case. Further, the holes have become less triangular, reducing the sharp corners in the topology. The strain energy distribution on the initial, uncoupled and coupled topology is given in Figure 3.

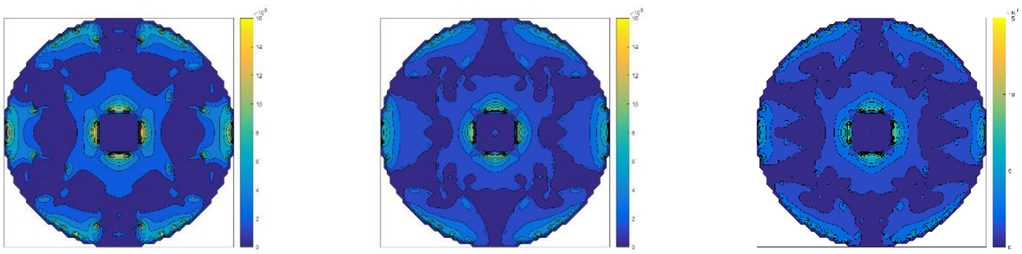

Figure 3. Initial Compliance (left) Final Compliance Uncoupled (middle) Final Compliance Coupled (right).

The initial strain energy distribution shows several concentrated regions around the holes, where the overall stress is significantly higher compared to the rest of the structure. Comparatively, the optimized topology significantly reduces these concentrated zones (Figure 3), especially if the center hole is ignored, since this region is non-designable. The coupled solution further reduces the strain energy concentrations, compared with the uncoupled solution.