A flexible magnetically-controllable fluid transport system

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ABSTRACT
The goal of this study is to understand the mechanics of a flexible magnetically-controllable fluid transport system. A two-dimensional time-dependent model using a coupled fluid-solid and magnetic model is developed. The flow of fluids through sinusoidal wall is modeled, numerically analyzed and compared with an analytical solution, for the passive case (i.e., zero applied magnetic field). The modeling and analysis are extended to include a magnetic field that is applied to the wall of the flexible tube in order to produce the one-way forward movement of the fluid. Results demonstrate the fluid transportation capabilities of the one-way transport system.

Keywords: Soft magnetorheological elastomer, fluid structure interaction, magnetically controllable

1. INTRODUCTION
An applied magnetic field can produce significant deformation in the magnetically permeable materials. Wang et al. presented a design for an electromagnetically actuated micropump using magnetic membrane. Barham et al. studied the behavior of a pressurized magnetic membrane based on magnetoelasticity. Raikher et al. presented analytical formulation for the deformation instability of magnetic membrane within magnetic field. Angel implemented magnetic membrane in an adjustable mirror, and LaRocque et al. suggested a peristaltic actuator using polymer foam infused by a magnetorheological fluid.

To understand the mechanism of the fluid propulsion in the flexible magnetically-controllable fluid transport system (FMCFTS), an accurate model is needed that can capture performance. In some cases, the movement of solid boundary causes the fluid to move and the fluid finite element mesh should follow the movement of the corresponding solid domain. Arbitrary Lagrangian-Eulerian method is utilized to consider the fluid mesh movement. In finite element methods fluid-solid interaction analysis three types of elements need to be defined for the fluid domain, interface domain, and structure domain. The large displacement affects the fluid-solid interaction analysis and strategies.

In this study, performance of the proposed FMCFTS, which includes a soft magnetorheological elastomer membrane (SMREM), as the actuation element, is investigated using time-dependent magneto-fluid-structure interaction finite element methods. Combining magnetic, structure and fluid in such system has not been investigated and is the focus of this research. To investigate the effect of SMREM deflection on the net flow two micro channels with and without valves are considered. Results show that FMCFTS can generate a net flow, when the one-way valves are implemented.

2. MODELING AND ANALYSIS
A SMREM is considered to be made of a highly-elastic matrix with embedded micron size ferromagnetic particles. Once a magnetic field is applied to the SMREM, it deflects within a few milliseconds. Figure 1 shows large deformation of SMREM under a magnetic field. Such a movement is utilized to generate a micro-propulsion. The FMCFTS consists of a SMREM, passive rubber, and a series of one-way valves. The valves are flexible, which allow the fluid flow in and out depending on the movement of the SMREM wall. The magnetic field deforms the SMREM and the
pressure generated from this action pushes the fluid forward through a series of one-way valves. An electromagnet is designed to induce a strong enough magnetic field to actuate the SMREM. The electromagnet is located at a distance from the micro channel to simulate actual working condition. The cross-section of the two-dimensional (2-D) system is schematically demonstrated in Figure 2. To verify the flow analysis, a converging micro channel is analyzed numerically using COMSOL multi-physics software, and compared to an analytical solution\textsuperscript{12}, for sinusoidal-shaped walls, as shown in Figure 3.

![Figure 1. Large deformation of a SMREM.](image1)

![Figure 2. The two-dimensional model of the FMCFTS.](image2)
Figure 3. Sinusoidal-shaped wall micro channel with elliptical cross section: a=200μm b=100μm.

Figure 4 shows the comparison between the numerical and analytical results of a converging micro-channel for the input Reynolds number of 100 and the discharging fluid to the atmospheric pressure. As can be seen, the numerical results of both the maximum pressure and the pressure drop after the minimum diameter agree well with the analytical results.

Figure 4. Pressure gradient of sinusoidal-shaped wall micro channel with elliptical cross section a=200μm b=100 μm.

Figure 5 shows the velocity and pressure drop of the sinusoidal-shaped wall micro channel. As can be seen, the velocity and pressure changes are consistent with the Bernoulli’s principal. It is shown that the maximum velocity along with zero pressure occurs slightly after the minimum cross section of the channel.

Figure 5. Velocity and pressure distribution of sinusoidal-shaped wall micro channel with elliptical cross section a=200μm b=100 μm.
The FMCFTS propels the fluid via the controllable magnetic actuation, and that the magnetic field is coupled with the solid and fluid domains. The SMREM channel is placed 6mm above the top of the electromagnet. Figure 6 (b) shows the magnetic flux density inside the wall of the SMREM with an average of 0.45T magnetic flux density. The Arbitrary Lagrangian-Eulerian moving mesh method is used to simulate the fluid-solid interaction. In COMSOL the magnetic, fluid, and structural modules along with the Arbitrary Lagrangian-Eulerian module were utilized to combine the effect of moving solid boundary on the boundary with the fluid. The deflection of the micro channel depends on the magnetic flux density and stiffness of the SMREM channel. To observe this effect, the input velocity is considered to be zero and the velocity generated due to the external load on the boundary is determined. Load is applied as a sinusoidal body force on the top wall of the channel for one second. Figure 7 demonstrates the fluid velocity generated and the solid boundary displacement in at t=0.25s, which corresponds to the maximum velocity. The modeled channel has the width of 3 mm, channel inner width of 400μ and the wall thickness of 100μ. Large deformation is considered for this analysis. Since the input velocity is zero, the amount of flow that is passing through the outlet depends only on the deformation of the solid domain. As can be seen in Figure 8 (a) the maximum flow occurs before 0.1s and the flow returns to the channel as the solid boundary retracts to original position. Figure 8 (b) shows the amount of fluid volume pumped at each time period.
Figure 8. (a) The outflow, and (b) transferred fluid at each time period generated by wall movement.

As the channel retracts, the transferred flow returns to the tube due to the negative pressure. To prevent the fluid returning to the channel, two conical valves are implemented which are shown in Figure 9. Adding the valves increases the maximum velocity occurring at the t=0.25 second since they reduce the fluid transport cross section.

Figure 9. Fluid proportion with zero input velocity.

Figure 10 (a) and (b) show the flow rate and total flow transported by the tube with two valves. From Figure 10 (a) it can be seen that the backward flow rate reduces significantly by the adding the valves. Also, Figure 10 (b) shows that adding valves produces a net flow transferred to the right as opposed to Figure 8 (b) in which all the transferred flow returns to the tube as a result of retraction.

The volume of transported fluid depends on the stiffness of the solid domain, dynamic viscosity of the fluid, valve geometry, the materials and geometric properties of the channel, and the applied magnetic field intensity. Adjusting the parameters and selecting the desired value of these parameters can result in maximum volume of the fluid transported by the FMCFTS.
A flexible magnetically-actuated fluid transport system is presented, modeled and numerically analyzed. The flexible micro tube is considered to be made of soft magnetorheological elastomer membrane. A magnetic-elastic-fluid coupling model was produced and numerically solved using COMSOL multi-physics finite element package. The results for the passive system (no magnetic field applied) show good agreement with an analytical solution. The effect of magnetic field on the tube’s wall is investigated for valveless and valved configurations to observe the volume flow rate that such a system can propel. Results show the capability of the system to propel fluid when the parameters are designed appropriately.

REFERENCES