A FLUID-STRUCTURE INTERACTION BASED SIMULATION STUDY OF PIEZOELECTRIC MICROPUMP FOR DRUG DELIVERY APPLICATION

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Abstract. Micropump technology has garnered the attention of researchers because of its diversity in numerous applications. Fast response and low power consumption make the piezoelectric micropump an obvious choice for controlled drug delivery applications. It requires fluid flow with minimum flow pulsations and backpressure. Because of the complex structure of the valved micropump, an accurate analytical flow solution is difficult to attain. Hence, a numerical simulation was performed on the model of piezoelectric micropump with microvalve using a finite element solver. A 3D Two-way Fluid-Structure Interaction (FSI) study was carried out. This illustrates the pressure exerted by fluid onto the solid and the change in fluid flow as the resultant. The solution was obtained for the fluid flow in a continuously deforming geometry. The analysis of results gives stresses developed on the microvalve, change in flow discharge and actuator displacement with respect to input frequency and voltage. The experimental results are presented to validate the simulation. This study is useful to establish a precise and controlled drug delivery using micropump in biomedical applications.

1. INTRODUCTION

A drug delivery system (DDS) consists of a method or a device that introduces the drug into the body. To improve the therapeutic index of the drug, it is very crucial for DDS to perform with optimum efficiency. The performance of DDS depends on the place, time and rate of the drug delivery. The drug delivery system is broadly classified into a sustained/ controlled drug delivery system and periodic/manual drug delivery. To achieve controlled or sustained drug delivery, it is important that flow should be with minimum flow pulsation and backpressure. A piezoelectric micropump is used in this study for simulation and experiment as shown in Figure 1.

![Figure 1. A Piezoelectric Micropump](image-url)

Large actuation time and rapid response make the piezoelectric micropump a vital component for drug delivery system. Specifications of the micropump components are tabulated in Table 1.
Table 1. Specifications of the Piezoelectric Micropump

| Piezoelectric Micropump | Values         |
|-------------------------|---------------|
| Fluid flow rate         | 20ml/min      |
| Drive frequency         | 10-60Hz       |
| Drive voltage           | 60-250Vp-p    |
| Maximum pressure        | 35KPa         |
| Physical dimensions     | 33×33×5.5mm   |

As compared to valveless micropump, a micropump with valves has the advantage in reducing the backpressure of the fluid. The pump houses 3 layers of material- PZT(Lead Zirconate Titanate) actuator, a diaphragm, and a metal plate.

Moreover, Traditional fluid flow simulation does not consider the FSI(Fluid-Structure Interaction) phenomenon. FSI is the multiphysics coupling between fluid mechanics and structural mechanics. It takes place between the moving structure and the surrounding fluid flow. If the deformations of the structure are large, the velocity and pressure field of fluid will change as a result and the problem becomes bi-directionally coupled FSI. In this, the fluid field and pressure field affect the structural deformation and structural deformation affects the flow and pressure. In the micropump, fluid mesh near structure undergoes large deformation and becomes distorted. (ALE formulation) Algebraic Lagrangian-Eulerian (ALE) provides undistorted mesh for the fluid around corners.

FSI is an important phenomenon to analyse the flow behaviour of the micropump. Alongside fluid mechanics and structural mechanics, flow simulations of piezoelectric micropump also consist of electromechanics. The working performance of the micropump can be improved by demonstrating the indicative parameters such as backpressure, pressure behaviour inside the system, flow rate and actuation pressure. [1] FSI is further classified as one-way coupling and two-way coupling. Two-way coupling is difficult to attain prior to its complex geometry, intricate physics of fluids and complicated fluid-structure interaction. [2] But two-way FSI is also helpful in quantifying and parameterizing the flow and pressure quantities for any real-time problems. [3] So the objective of using FSI changes with the change in application. In the case of piezoelectric micropump, FSI is being used in simulation study of both valveless and microvalve pumps. [4] FSI can also be used to confirm the experimental results. [5] Simulation study to understand the flow pulsation and backpressure from the human body are not well explored. A simulation model on 3D piezoelectric micropump is a challenging task.

An attempt has been made in this paper to simulate and control a piezoelectric micropump to obtain a solution for fluid flow in a continuously deforming geometry. 3D two-way fluid-structure interaction is carried out to obtain stresses developed on the microvalve, change in flow discharge and actuator displacement with respect to the given input frequency and voltage. In this paper a simulation study based on 3D two-way FSI of piezoelectric micropump with microvalve is conducted. The analysis of backpressure, flow characteristics and the pressure parameters are presented for the developed 3D simulation of FSI model.

2. 3D MODELING

2.1 Structure of the Piezoelectric Micropump

The Piezoelectric micropump selected for the study has a single chamber with inlet and outlet. The structure of the pump consists of a piezoelectric actuator disc. Also, the pump houses a 3 layer structure with a diaphragm and a metal plate placed underneath the piezo actuator. The piezoelectric pump is a unimorph with just a single layer of piezo actuator. This micropump contains 2 microvalves to curb the amount of backpressure. Figure 2 depicts the structure of the micropump-
2.2 3D Model of the Piezoelectric Micropump

The 3D solid model of the piezoelectric micropump (figure 2) is built in the COMSOL Multiphysics package. Piezoelectric actuator is made up of PZT (Lead Zirconate Titanate) material. The pump diaphragm and pump housing uses COC material. The inlet and outlet microvalves are flexible. The microvalves were made from EPDM (ethylene propylene diene monomer). These valves are deflected by the velocity and pressure exerted by the fluid. Simulation is performed using this 3D model of piezoelectric micropump.

3 Dimensional two-way FSI was carried on the piezoelectric micropump to obtain the simulation results for fluid flow and von mises stress results.

3. RESULT AND DISCUSSION

3.1 Simulation of Piezoelectric Micropump

The micropump selected for the study works on piezoelectric actuation. Piezoelectric pumps are simple in structure, lightweight and it can handle small quantity of water. These attributes makes it an obvious choice. Simulation of piezoelectric micropump involves the multiphysics approach wherein different physics are combined together to perform the simulation. This study involves the electric-fluid-structure interaction approach. Structural mechanics, electrostatics and fluid dynamics are combined together to get the results for flow rate and stress concentration of the pump. Table 2 shows the change in flow rate with respect to input voltage.
Table 2. Fluid flow rate vs Voltage input

| Voltage in V | Frequency in Hz | Volume in ml | Time in Min | Flowrate ml/min*10^-5 |
|--------------|-----------------|--------------|-------------|-----------------------|
| 100          | 20              | 10           | 1.35        | 2.25                  |
| 150          | 20              |              | 47.94 sec   | 1.95                  |
| 200          |                 |              | 28.86 sec   | 1.5                   |
| 250          |                 |              | 23.93 sec   | 1.2                   |

The simulation results for flow rate indicate that it is in proportion with change in input voltage and frequency.

3.2 Simulation of Piezoelectric actuator

Piezoelectric actuator used in the micropump is unimorph i.e. the pump uses only one layer of the piezoelectric material. The piezoelectric layer uses PZT (Lead Zirconate Titanate) material. The piezoelectric material is bonded to a diaphragm and a metal plate. The structure of the piezoelectric actuator is shown in figure 4. The actuation of the piezoelectric material is carried out by applying the potential to the top of the piezoelectric material. The piezoelectric material deforms along with the metallic plate and the diaphragm.

\[ V_0 \sin(20 \times t / s) \]  

Where \( t \) stands for time in seconds and \( s \) stands for the frequency in Hertz. The effect of variation of input voltage on the deflection of the diaphragm can be seen in Figure 4.

Figure 4. Simulation of the piezoelectric actuator
3.3 Simulation of Microvalve

The micropump contains two microvalves in the structure. Figure 6 gives the von mises stress distribution in the microvalves. These valves are placed to minimize the backpressure. The valves are placed at the inlet and the outlet of the pump. As per the structure of the pump, the inlet and outlet of the pump are predefined. The position of the valves is inverted to restrict the flow of the water in only one direction. As compared to the valveless micropump, this valved structure aids in better backpressure control and ensures the unidirectional flow.

Figure 5. Displacement of Piezoelectric Actuator

Figure 6. Simulation of the microvalve(a) deflection of the microvalve(b) Two microvalves in position.
3.4 Experimentation
For the validation of the simulation results, experimentation is carried out. Experimental setup involves the piezoelectric micropump, a controller to vary the voltage input to the pump, the input-output reservoir and tubing to connect the pump to the reservoir. Input voltage is varied from 60Volts to 250Volts and frequency is kept constant at 20Hz to match the simulation scenario. The flow rates are calculated for pumping 10ml of water. Table 3 shows the flow rate variation for different sets of voltage and frequency.

| Piezoelectric Pump | Voltage in V | Frequency in Hz | Volume in ml | Time in Min | Flowrate in ml/min |
|--------------------|--------------|-----------------|--------------|-------------|-------------------|
|                    | 100          | 20              | 10           | 1.35        | 7.4               |
|                    | 150          |                 |              | 47.94sec    | 12.5              |
|                    | 200          |                 |              | 28.86sec    | 20.79             |
|                    | 250          |                 |              | 23.93sec    | 25.07             |

4. CONCLUSION
A 3 dimensional solid model for piezoelectric micropump is modeled in COMSOL Multiphysics package. Simulation is carried out on a finite element model. Simulation of micropump contains electro-fluid-structure interaction study. This study is a bidirectional electro-fluid-structural interaction. This gives the flow rate and backpressure distribution in various parts of the micropump. Also, the results indicate that flow rate, actuation of piezo element and backpressure developed are directly proportional to the voltage and frequency input. This study will be helpful in designing the various types of external and implantable micropumps for drug delivery application. The future scope of this research includes further optimization and finetuning of the model to get the accurate flow output with minimum backpressure.

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