Design and Simulation of A Piezoelectric Actuated Valveless Micropump

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Abstract: In this work, we design and simulate a valve less, diaphragm-based, piezoelectric micro pump. The piezoelectric actuator is a PZT-5H piezo-disk, the diaphragm is a borosilicate glass plate. All the simulations were made using COMSOL Multiphysics software. First, the piezoelectric actuator and membrane thicknesses were chosen by means of a stationary simulation, using the piezoelectric devices module we simulate the deformation of the membrane under different voltages, using different combinations of membrane and piezo actuator thicknesses. From the obtained results we decided to use a 100 µm membrane and a 50 µm piezo actuator. Using this geometry we build a simplified symmetric 3D model to be used in the pump simulation. A complete system simulation with one way coupling between the piezoelectric devices module and the fluid structure interaction module was made. It is considered to have no back-pressure. The results obtained for inlet, outlet and net flow are showed in this document.

Keywords: MEMS, micropump, valveless, piezoelectric.

1. Introduction

Microfluidics is a multidisciplinary field, basically it designs systems to handle small volumes of fluids. Some of the applications are inkjet print heads, DNA chips, lab on chip technology, micropropulsion, drug delivery, and micro thermal technology.

Most of microfluidic applications require a pumping action in order to move the fluid through the system. Some applications can make use of surface tension, macroscale pumps, positive or negative pressure chambers or other methods to transport the fluid. Yet, for most applications a micro scale active pump is highly desirable.

A piezoelectric micropump is modeled, the actuator is a PZT-5H piezo-disk and the diaphragm is a borosilicate glass plate. COMSOL Multiphysics was used to choose the right membrane to piezo thickness relation and to simulate the pumping system under a sinusoidal voltage applied to the piezo actuator.

2. Governing Equations

A piezoelectric material is capable of converting electrical energy into mechanical energy and vice versa. The direct piezoelectric effect states that these materials, when subjected to mechanical stress, generate a proportional electric charge. Gas lighters, acceleration and pressure sensors make use of the direct piezoelectric effect. The inverse piezoelectric effect states that the same materials, when subjected to and electrical field, become proportionally strained. Buzzers and force sensors use the inverse piezoelectric effect. The linear piezoelectric constitutive strain-charge relations for isothermal conditions using contracted matrix notation are:

$$S_{ij} = s^E_{jk} T_k + d_{kj} E_k \qquad (1)$$

$$D_i = d_{ij} T_j + \epsilon^T_{ij} E_j \qquad (2)$$

where S is the mechanical strain, s^E is the elastic compliance coefficient at constant electric field, T is the mechanical stress, d is the piezoelectric strain coefficient, D is the electric displacement and ϵ^T is the permittivity at constant stress.

Piezoelectric strain coefficient matrix for PZT-5H is as follows:

$$[d_{ij}] = \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{31} \\ 0 & 0 & d_{33} \\ 0 & d_{15} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$d_{31} = -274 \times 10^{-12}\, CN^{-1}$$
$$d_{33} = 593 \times 10^{-12}\, CN^{-1}$$
$$d_{15} = 741 \times 10^{-12}\, CN^{-1}$$

If there is no residual stress, the first term of right side of Equation (1) is equal to zero, also for a thin circular membrane one can assume that the strain is produced only in the radial direction. The simplified relation becomes:

$$S_1 = d_{31}E_3 \tag{3}$$

The behavior of the electrostatic part of the system is described by Maxwell laws:

$$\nabla \cdot \mathbf{D} = \rho_v \tag{4}$$

$$\mathbf{E} = -\nabla V \tag{5}$$

In this case, as showed in Figure 1:

$$E_3 = \frac{V}{t_p} \tag{6}$$

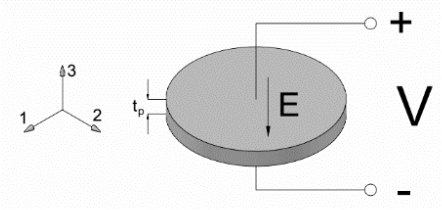

Figure 1. Schematic of the actuation system.

The elastic behavior of the membrane is described by Newton second law:

$$\rho\frac{\partial^2\mathbf{u}}{\partial t^2} - \nabla\cdot\boldsymbol{\sigma} = \mathbf{F}_v \tag{7}$$

where ρ is the density of the solid, **u** is the solid displacement vector, $\boldsymbol{\sigma}$ is the stress tensor and $\mathbf{F}_v$ is the body force per unit volume.

Incompressible fluid motion is described by Navier-Stokes equations as:

$$\rho\left(\frac{\partial\mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}\right) = \nabla\cdot[-p\mathbf{I} + \eta(\nabla\mathbf{u} + (\nabla\mathbf{u})^T)] + \mathbf{F} \tag{8}$$

where ρ is the density of the fluid, **u** is the fluid velocity vector, p is the pressure, η is the viscosity and **F** is a vector that represents all the external forces.

The continuity equation states that:

$$\nabla\cdot\mathbf{u} = 0 \tag{9}$$

For irrotational flow of incompressible liquids the Navier-Stokes equations can be reduced to the Euler equation as follows:

$$\rho\left(\frac{\partial\mathbf{u}}{\partial t} + \frac{\nabla\mathbf{u}^2}{2}\right) = \nabla(-p - \rho gz) \tag{10}$$

then integrating this equation between to points of the streamline Bernoulli equation is obtained:

$$\int_1^2\left[\rho\left(\frac{\partial\mathbf{u}}{\partial t}\right) + \nabla\left(\rho\frac{\mathbf{u}^2}{2} + p + \rho gz\right)\right]dl = 0 \tag{11}$$

in steady state and fully developed flow, this equation becomes:

$$\left(\frac{\mathbf{u}^2}{2} + \frac{p}{\rho} + gz\right)_1 - \left(\frac{\mathbf{u}^2}{2} + \frac{p}{\rho} + gz\right)_2 = 0 \tag{12}$$

then adding the contribution of any external force present in our system we obtain:

$$\left(\frac{\mathbf{u}^2}{2} + \frac{p}{\rho} + gz\right)_1 - \left(\frac{\mathbf{u}^2}{2} + \frac{p}{\rho} + gz\right)_2 = -h_P + h_f + h_L \tag{13}$$

where h_P is the sum of the head gains of the pumps, h_f is the sum of the head losses because of pipe friction and h_L is the sum of the head losses in the accessories.

3. Principle of operation

The basic principle behind the operation of this pump is the difference between pressure losses in different kinds of accessories, the nozzle/diffuser is considered an accessory inside the Bernoulli equation (13), and is defined as:

$$h_L = k\frac{\mathbf{u}^2}{2} \tag{14}$$

the way the accessory behaves only depends of the flow direction on each instant, so each nozzle/diffuser accessory behave as a nozzle when the direction of flow is as showed on Figure 2 and like a diffuser when the flow direction is as showed in Figure 3.

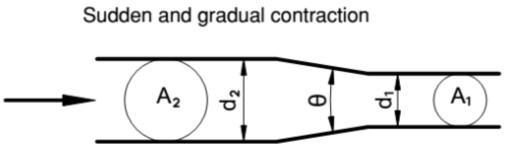

Figure 2. Nozzle behavior.

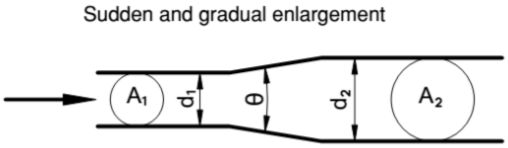

Figure 3. Diffuser behavior.

The value of k can be even one order of magnitude larger for nozzle behavior than for diffuser behavior. Taking this into account it is clear that when the membrane move upward the fluid is absorbed on both ends, but the pressure drop on the outlet is bigger, because it is acting as a nozzle. As a consequence there is a larger volume of fluid being absorbed in the inlet in comparison with the outlet (Figure 4).

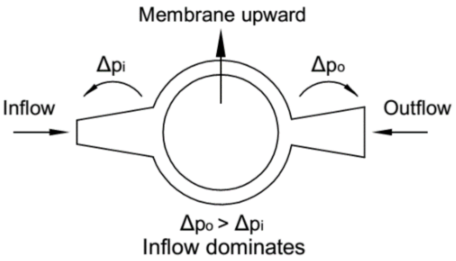

Figure 4. Upward movement of the membrane.

On the other hand, when the membrane is moving downward, the opposite will occur, now the inlet is acting as a nozzle, having a larger pressure drop, thus the larger volume is being expelled in the outlet.

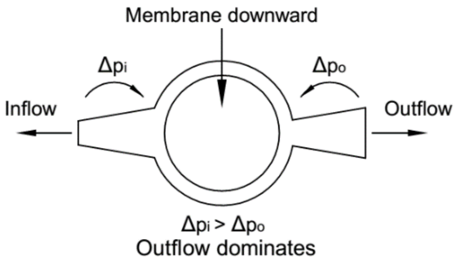

Figure 5. Downward movement of the membrane.

4. Use of COMSOL Multiphysics

The model of the pump was sliced to use a symmetry condition, this way the obtained 3D geometry is showed in Figure 3. Also the body of the pump, and the rest of the membrane were eliminated and instead of that a direct no-slip condition and a fixed boundary condition were used respectively.

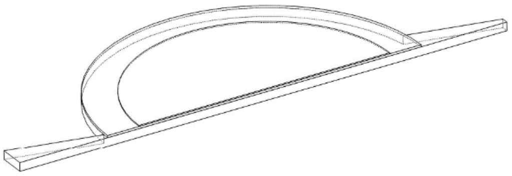

Figure 6. Symmetric model of the pump.

Solid mechanics (*solid*), electrostatics (*es*) and fluid structure interaction (*fsi*) were used to simulate the fluid motion in the pump. The piezoelectric effect was used, but it was necessary to manually add a coupling between *solid* and *fsi.* Two different studies were used, one for *es* and *solid*, and the other for *fsi* using the not-solve variables from previous study, in this way, a one-way coupling was achieved.

Although it is known that many of the process that involve flow of small volumes are considered as Stokes flow (inertial forces << viscous forces), in this case the principle of operation itself is based on the acceleration and deceleration of the fluid in the nozzle/diffuser, therefore it would be an error to assume that in the simulation.

5. Results

First, a parametric stationary study was made to determine the best geometry of the pump (Figure 7), from this data, a 100 µm membrane and a 50 µm piezo disk were chosen. Then the complete flow motion simulation was made using a frequency of 30Hz and a voltage of 30V, inlet and outlet flow rates, netflow and pumped volume are showed on Figures 8 and 9. The flow rates were intentionally put on phase by adding a minus sing to the inflow in order to easily see their difference. The average flow rate of the pump under this conditions is approximately 8.95 mm^3/s. More data from other frequency and voltage combinations is expected on the short term.

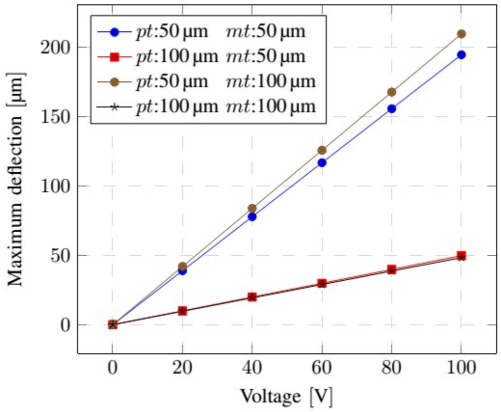

Figure 7. Maximum deflection of the membrane under variable applied voltage for four different conditions. Here, *pt:* piezoelectric thick, and *mt:* membrane thick.

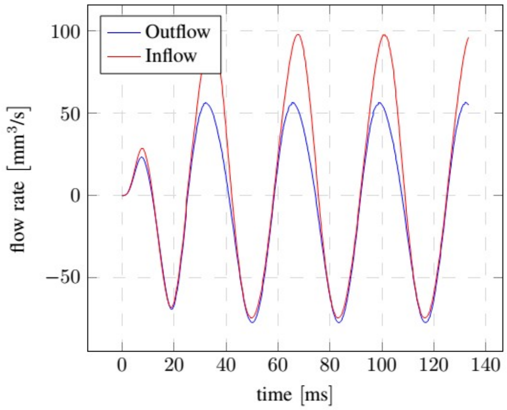

Figure 8. Flow rates, *f*=30Hz, V=30V.

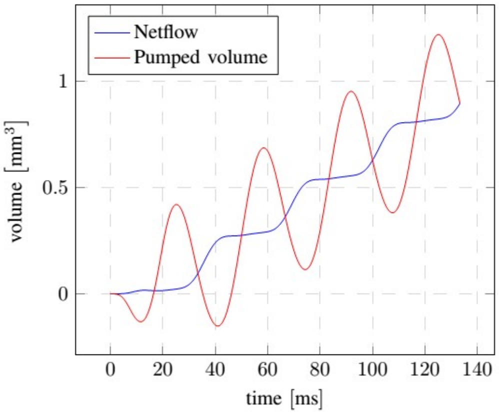

Figure 9. Netflow and pumped volume, *f*=30Hz, V=30V.

A 3D printed prototype of the pump is under development (Figure 10), it will be used to obtain experimental data in order to verify this results. Figure 11 shows the differences in pressure drop during the downward cycle as expected.

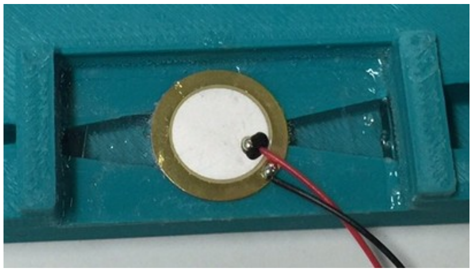

Figure 10. 3D printed prototype under development.

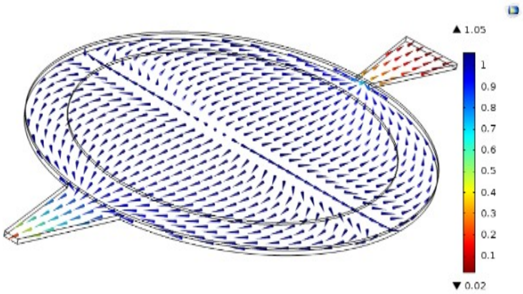

Figure 11. Pressure in kPa in the downward movement.

6. Conclusions

A one-way coupled simulation of fluid motion in a piezoelectric valveless pump was successfully made using COMSOL. A simply stationary study has proven to be a useful first approach to make decisions about the geometry of the pump.

7. References

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