Proof of Concept and Properties of Micro Hydraulic Displacement Amplifier

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Abstract:

Nowadays, mathematical models have been widely applied in varies fields; especially in fluid mechanics and nonlinear material which are very complex or even not possible to be calculated using analytical methods. In this paper, a hydraulic displacement amplifier coupled with fluid mechanics and hyperelastic material is studied through 2D axisymmetric FSI (Fluid-structure interaction) model in COMSOL using Navier-Stokes and Mooney-Rivlin approaches. The displacement amplification based on encapsulated fluid, which works as a medium to transfer the required power for hydraulic actuation in microscopic range, is investigated. The actuation behaviors, the liquid movement inside of the chamber, the pressure distribution and the amplification ratio, are studied and discussed.

Keywords: Hydraulic, Displacement amplifier, Amplification, FSI, Fluid-structure interaction

1. Introduction

In recent years, microhydraulic principle, which can be used to transfer power and displacement, has been gradually used in Micro Electro Mechanical Systems (MEMS). As shown in Figure 1, the liquid is encapsulated and sealed in a chamber with hyperelastic membranes from both sides of the chamber. The displacement of the upper membrane occurs when certain uniform pressure supplied by a driver, e.g. pneumatic pressure is applied to the lower membrane. Due to the difference in membranes' areas, the deflection of the upper membrane is higher than the deflection the down membrane, thus the deflection of down membrane is amplified. Tactile actuators used in navigation systems or reading devices for visually impaired people can be famous application examples [1, 2, 3, 7].

To design an amplifier, understanding its mechanical behavior is the first step. In this case, in a special tactile actuator investigated by Furtwangen University, the deflection of upper membrane has to be above 50 µm. Therefore, the desired driving force needs to be characterized to select the proper driver. Since amplifier and driver are in microscopic scale, the whole system has to obey the scaling law. In another word, the force generated by the driver diminishes exponentially by reduction of dimensions [2]. In order to use the efficient force to get sufficient amplification ratio, it is necessary to characterize the amplifier.

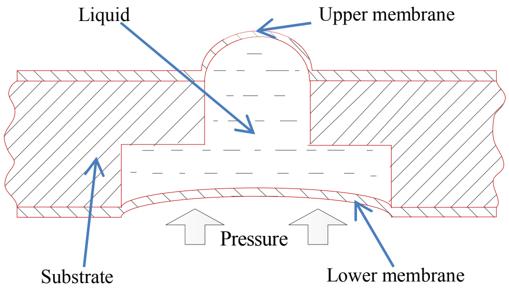


Figure 1. Schematic of the cross section view of a hydraulic displacement amplifier

2. Amplifier Model and Governing Equations

An amplifier consists of a chamber that is filled with silicone oil and sealed by two membranes is assumed for the simulation. Silicon and PDMS are chosen as the materials of the chamber and membranes, respectively. To define the liquid inside of chamber, Navier-stokes equation is employed. Since the PDMS is an elastomer material, the hyperelastic model (Mooney-Rivlin model) is coupled to the model as well.

Therefore, the governing equations are:

Ⅰ. Navier-Stokes equation [5, 6]:

$$\frac{\partial \vec{u}}{\partial t}+\vec{u}\cdot\nabla\vec{u}+\frac{1}{\rho}\nabla p=\vec{g}+\nu\nabla\cdot\nabla\vec{u} \tag{1}$$

$$\nabla\cdot\vec{u}=0 \tag{2}$$

$\vec{u}$	Velocity of fluid
ρ	Density of fluid
p	Pressure that the fluid exerts on anything
t	Time
$\vec{g}$	Body force applied on fluid
ν	Kinematic viscosity of fluid

The liquid is assumed to be incompressible and expressed by eq. 2. The boundary condition for liquid can be expressed through eq. 3 and eq. 4. The velocity of liquid at wall is assumed to be zero, and the velocity of liquid at the interface between structure and liquid is set the same as the movement speed of structure.

$$\vec{u}=0 \tag{3}$$

$$\vec{u}=\vec{u}_{solid} \tag{4}$$

Ⅱ. Mooney-Rivlin equation [4]

Compared to Yeoh and Ogden model, the Mooney-Rivlin model, the most widely used strain energy function in FEA, is chosen due to its simplicity and robustness. Although it is inadequate in describing the compression mode of deformation, and fails to account for the stiffening of the material at large strains, it shows a good agreement with tensile test up to 100% strain. Hence, the two coefficients Mooney-Rivlin model is used, and the governing equations are:

$$W=C_1J_1+C_2J_2 \tag{5}$$

$$\begin{aligned} J_1&=\lambda_1^2+\lambda_2^2+\lambda_3^2-3\\ J_2&=\lambda_1^2\lambda_2^2+\lambda_2^2\lambda_3^2+\lambda_1^2\lambda_1^2-3\\ J_3&=\lambda_1^2\lambda_2^2\lambda_3^2-1 \end{aligned} \tag{6}$$

W stands for the strain energy density, λ_i denotes the principal stretch ratios, defined as the ratio of stretched length to upstretched length of the edges of a small volume element, cubical in the unstrained state. The value of λ_i are given by $1+\varepsilon_i$ where ε_i is the corresponding principal extension, and C_1 and C_2 stand for the material constant.

3. Use of COMSOL Multiphysics

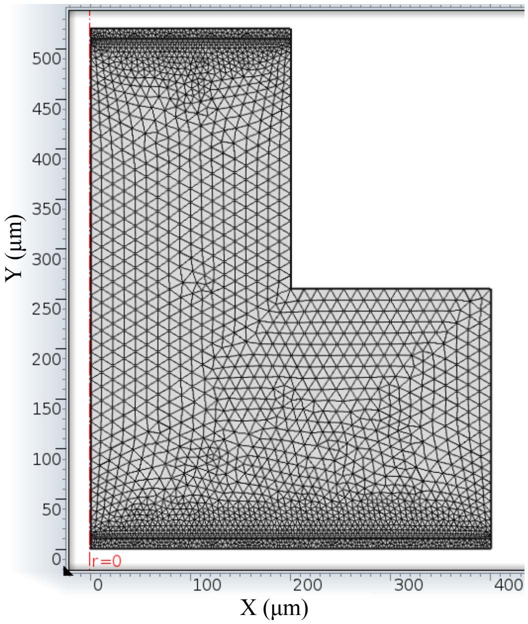


Figure 2. Example of the meshed step wall model in Comsol (membrane thickness: 10 µm)

2D axisymmetric fluid-structure interaction finite element simulation of an amplifier is implemented in COMSOL, and the sets of equations mentioned in previous section are coupled in the FSI model. The model is consisted of an upper cylinder with radius of 200 µm and lower cylinder with radius of 400µm. Both cylinders have a height of 250µm which makes the total height of chamber the same as the thickness of standard silicon wafer (500µm). The PDMS, which is mix of base polymer and curing agent with ratio of 5:1, with bulk modulus (1214.84MPa), C_1 (0) and C_2 (0.1342MPa), is chosen as the material of both membranes [9]. The thickness of both membranes is assumed to be the same and varies from 10µm to 50 µm by step of 10 μm. Silicon oil is assumed as the encapsulated liquid, and its density (120 Kg/m³) and viscosity (1.49e-3Pa·S) almost have no influence on the simulation results. The whole structure is meshed by already built in finer physics control mesh and shown in Figure 2. Finally, the simulation is done using "time dependent" solver. The pressure applied on the down membrane is varied using ramp function, which results in rise of pressure from 0 to 10KPa in the first second and holds this value for 2 seconds.

4. Results and Discussions

4.1 Liquid movement

The liquid inside of amplifier acts as transfer medium for power, hence it is necessary to study the movement of liquid inside of amplifier to observe the power transportation from down membrane to upper membrane. As shown in Figure 3, since both membranes are fixed only at the edges, the deflection of both membranes near the edge is less than the one in the center, which results in a low velocity of liquid at edge. The liquid is driven up and accumulated very close to upper membrane, thus the maximal movement velocity appears at the middle under the membrane (dark red part). Meanwhile, the maximal velocity depends on the driven velocity, even so, the maximal velocity of liquid is only about hundreds micrometer per second in this case.

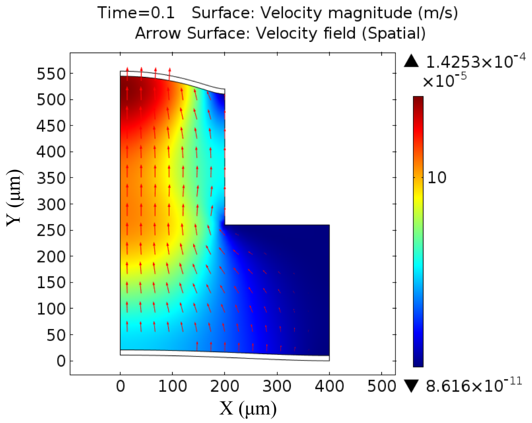


Figure 3. Liquid movement inside of amplifier (membrane thickness: 10 μm)

4.2 Pressure distribution

The pressure distribution in the amplifier after actuation and stabilization is shown in Figure 4. The pressure inside of liquid is homogeneous and it is almost equal to the maxilmal pressure (10KPa) applied on the amplifier. The pressure is greater than the maximal pressure can be considered as simulation error. Here it is asumed that the total pressure is equal to the pressure on the lower membarne plus the pressure on the upper membrane. Since the sum of pressures on the lower membrane (driven pressure and pressure inside of the fluid) is almost equal to zero, the total pressure will be applied to the upper membrane. Therefore, to analyze deflection of the amplifier the easiest way is to analyze the deflection on the upper membrane only. Since the highest stress is at the edge of upper membrane, where the interface between membrane and silicon substrate is. The adhesion of PDMS membarne onto the silicon substrate should not be lower than 406 KPa.

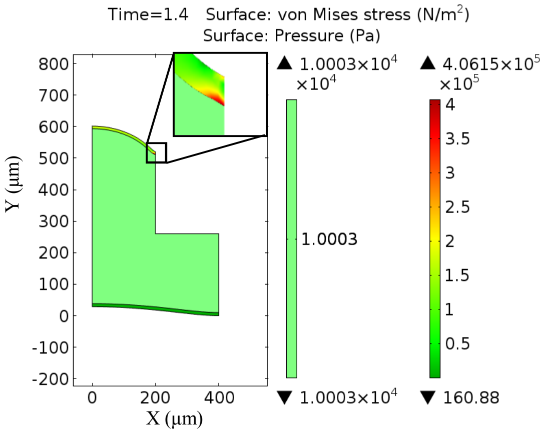


Figure 4. Pressure distribution in amplifier (membrane thickness: 10 μm)

4.3 Amplification ratio

Amplification ratio is defined as the ratio of the center deflection of upper membrane to the center deflection of lower membrane and indicates the amplify ability of the amplifier. Amplification is a key parameter to describe an amplifier.

Based on the simulation reuslts, it is found that the amplification ratio jumps from zero to a certain value (between 3.5 and 4 in this case) once the pressure is applied, and then drops with the increase of applied pressure (Figure 5). Larger membrane thickness results in slower decrease of amplification ratio; when membrane thickness is larger than 20 µm, the maximal amplification ratio decreases.

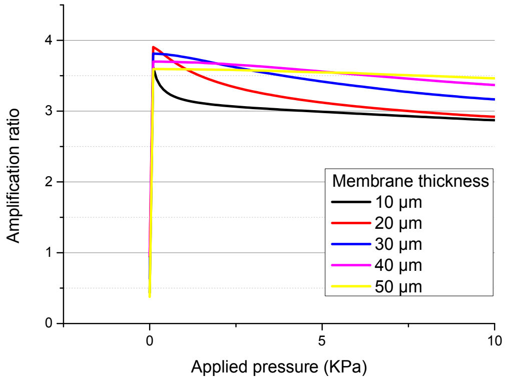


Figure 5. Amplification ratio versus applied pressure

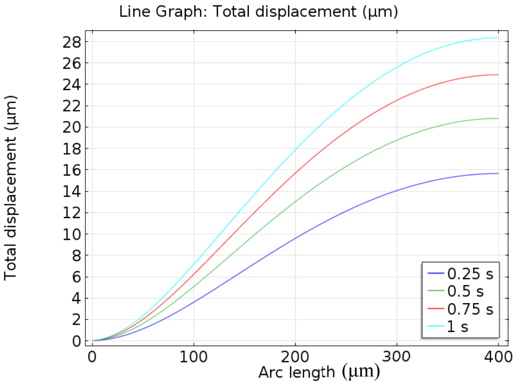


Figure 6. Deflection of lower membrane (legend indicates the time)

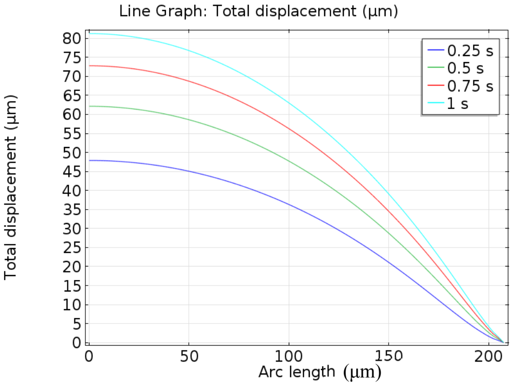
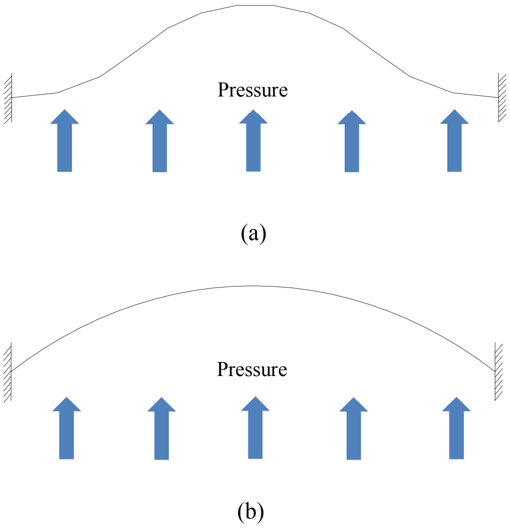


Figure 7. Deflection of upper membrane (legend indicates the time)

The droping of amplification ratio could be explained by the deflection behavior of membrane. To ease of understanding of this phenomenon, the deflection index is introduced. The deflection index is defined as deflection over the radius of membrane and indicates the deflection amount of membrane.

As an example, for the membranes with thickness of 10µm, the deflection of the upper membarne after 0.25 s is 47µm whereas the deflection of the lower membrane is 15.6µm (see Figure 6 and Figure 7); however their deflection indexes are 0.235 and 0.039, respectivly. Thus, the deflection amount of upper membrane is relatively larger than the lower membrane.



(a)

(b)

Figure 8. Schematic cross section view of deflected membrane at different stages

As it can be seen in Figure 8, when the deflection index is small, the cross section of membrane is similar to a quartic graph (Figure 8a). on the contrary, when the deflection index is large, the cross section of the deflected membrane looks like an arc (Fig. 8b). In other words, the deflection cross section view of membranes changes form (a) to (b) with the increasing of deflection. As a result, the membranes start to deflect form the center and then distributes further to the edges. Therefore, the lower membrane deflect faster compared to upper membarne which results in the droping of amplifiacation ratio.

In addition, when a membrane is thick, it is harder to deflect it. Thus, its deflction index increaseing is slower compared to a thin membrane. It is a reason why a thicker membrane has a lower maximum amplification ratio.

5. Conclusions

Micro hydraulic principle can be used in many applications with different structures. In this paper, the fluid movement, pressure distribution and amplification ratio of a micro hydraulic displacement amplifier is successfully studied and simulated by using FSI model in COMSOL.

Under the given parameters, the liquid inside of the chamber moves only in the direction of the membrane deflection. Since the maximal velocity of the liquid is quite small, it results in a very small viscous force. As the deflection of amplifier and its driven force highly depend on the upper membrane, these parameters should be analyzed carefully. In addition, the amplification ratio depends on the deflection index of the lower membrane.

6. References

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