Effect of flexure beam geometry and material on the displacement of piezo actuated diaphragm for micropump

Roopa R, Navin Karanth P, S M Kulkarni

Department of Mechanical Engineering, National Institute of Technology Karnataka, Surathkal, Srinivasnagar, Mangalore 575025, India.

E-mail: roopa.hassan89@gmail.com

Abstract. In this paper, we present a COMSOL analysis of flexure diaphragm for piezo actuated valveless micropump. Diaphragms play an important role in micropumps, till now plane diaphragms are commonly used in micropumps. Use of compliant flexure hinges in diaphragm and other MEMS application is one of the new approach to achieving high deflection in diaphragm at low operating voltage. Flexures hinges in diaphragm acts as simply supported beam. Out-of-plane compliance value and stiffness is considered for the selection of proper flexure for diaphragm. Diaphragm material also plays an important role in the diaphragm central deflection. Factor considered for diaphragm material selection is resilience; it is the ratio of yield stress to static modulus. Higher is the resilience will leads to higher deflection generated, it also imparts good compliance. Based on the resilience beryllium copper, stainless steel and brass materials are selected for diaphragm analysis. Simulations have been performed using COMSOL multiphysics. This study reports the effect of flexure hinge geometry and diaphragm material on the central deflection of diaphragms and compared with existing plane diaphragm. Simulation results illustrates that the deflection of three flexure diaphragm with 2mm width and 2mm length flexure is 6.75 µm for stainless steel, 10.89 for beryllium copper and 12.10µm for brass, at 140V which is approximately twice that of plane diaphragm deflection. The maximum in both plane and three flexure diaphragm deflection is obtained for brass diaphragm compared to stainless steel and beryllium copper.

Keywords: Piezo actuation; Flexure hinge; Micropump; Diaphragm; COMSOL

1. Introduction

Micropump is one of the MEMS devices which play an important role in microfluidic system application. Micropump play an vital role in field of chemical, biological, medical, electronics cooling and biomedical applications. Different numbers of micropumps have been designed in recent years based on the actuating principle, valves, and fabrication technologies. Micropumps are classified as mechanical and non-mechanical micropumps [1-2]. Mechanical micropumps are widely used since they are less reactive to liquid properties where as non mechanical micropump very sensitive. The actuation principle for mechanical type micropump are electrostatic [3], piezoelectric [4-5], electromagnetic [6], thermo-pneumatic [7] and shape memory alloy [8]. Piezoelectric actuation is most popular and commonly used earliest mechanism type of actuation for micropumps. Because they normally have high stroke volume, good reliability, energy efficiency, short response time, low power consumption and high actuating force [9]. The piezo actuator converts electrical signal to mechanical displacements. PVDF is widely used for the actuation of diaphragm because of lead component in PZT [19].

The work on the micropumps started since 1980, Smits [10] manufactured the piezoelectric actuated valve type silicon micropump, and later Olsson [11] introduced the valveless micropumps to reduce the clogging, wearing, and fatigue. Stemme E. and Stemme G. [12] designed a piezoelectric valveless micropump for the first time which can be fabricated easily compared to valve type micropumps. To
eliminate the residual stress in diaphragms Yang et al. [13] fabricated and tested the electrostatic actuated P+ silicon corrugated diaphragm for micropumps. Later Jeong et al. [14] introduced thermo pneumatic actuated P+ silicon corrugated diaphragm for valveless micropumps. Based on the previous studies, much work has not been done on the micropump diaphragms design. Different diaphragm materials are used for micropump application, based on the application and size of the micropump materials can be selected. Some of the commonly used diaphragm materials are silicon [3], glass [4], brass [12], beryllium bronze [15], PDMS [16], aluminum-Si [17] etc.

A mechanism which is composed of at least one component that is sensibly deformable or flexible compared to the other rigid links is called as compliant mechanism [18]. Compliant mechanisms provide guided motion via elastic deformation by use of flexure hinges. Their ability to produce repeatable/precise frictionless motion makes them a common choice in precision positioning devices, frictionless bearings, and biomedical devices. Compliance flexure hinge in design leads to joint less, no-assembly, monolithic mechanical devices and is particularly suited for application with small range of motions [21]. Now a day’s flexure hinges are used in the field of aeronautical, automotive, medical industries and in MEMS systems such as micro cantilevers, scratch drive actuator, sensors, accelerometers, gyroscopes, micro switches, tensional mirrors etc. [18]. Advantages of using compliant mechanism are low cost, increased performance, high precision and ability to miniaturize i.e. more suitable for MEMS and nano scale applications [18, 22]. Flexures in diaphragm are mainly used to provide out-of-plane motion in MEMS devices, actuators, sensors, flow control, frictionless linear bearing [23].

In this paper a flexure hinges are used in diaphragm to achieve high deflection in diaphragm at low operating voltage. This study reports the effect of flexure hinge dimension and diaphragm material on the central deflection of diaphragms and compared with plane diaphragm. Flexures are commonly used for providing motion in the direction normal to the flexure plane. Flexure hinge diaphragms are simulated with piezoelectric actuator using COMSOL multiphysics. Each flexure hinge is treated as a spring connected parallel to diaphragm, increase in the number of flexure hinges will make the diaphragm stiffer. Three flexure hinges are sufficient to get maximum deflection in diaphragm. The simulation results illustrate that the deflection of three flexure hinge diaphragm is approximately twice the deflection of plane diaphragm. Use of flexure hinges in diaphragm will provide guided motion via elastic deformation. This flexure hinge diaphragm can also be used for other MEMS application like sensing, bearing, RF switches etc.

2. Design of flexure hinge diaphragm

2.1 Selection of flexure hinges

Mainly there are three types of flexure hinges i.e. rectangular flexure hinge, corner fillet flexure and circular flexure hinges used in order to design a flexible based compliance mechanism. Based on the load applied to the flexure planes it is further classified into two types i.e. in-plane flexure mechanism and out-of-plane flexure mechanism. The active and resistive loads are in planar in case of in-plane flexures application where as in case of out off plane flexure application the loads are in perpendicular direction. Out-off plane compliance occur as a result of errors caused by defective actuation or positioning of external loads or manufacturing and assembly [18]. Rectangular cross section flexures have simplest geometry compared to all other hinges. Rectangular flexures hinges are widely used in out-off plane application, because of minimum stress concentration with higher deflection [18]. Flexural diaphragm is out-off plane compliance so rectangular hinges are more suitable for this application.
2.2 Selection of diaphragm material

Motion in the compliant mechanisms comes from bending of flexible parts, so this flexure hinge experience stress. This can be overcome by using certain materials, so selection of material plays an important role in compliant mechanism [20]. Some of the new materials are available which are well suited for compliant mechanisms. The desirable properties for the selection of material for compliant mechanism are resilience. Resilience is the ratio of yield stress to static modulus. Higher is the resilience higher is the deflection and force generated, it also imparts good passive compliance. Materials with large $\sigma_y/E$ values are generally good candidates for compliant mechanisms. If the $\sigma_y/E$ value is high then the material is said to be stronger and flexible. Table 1 shows the list of yield stress to young’s modules ratio and resilience of different materials selected for the micropump diaphragms.

Table 1. List of yield stress to young’s modules ratio and resilience of different materials.

| Material                     | Density (g/cc) | Yield stress $\sigma_y$ (GPa) | Modules of elasticity $E$ (GPa) | Resilience |
|------------------------------|----------------|-------------------------------|---------------------------------|------------|
| Beryllium copper (CA 170)    | 8.25           | 1.17                          | 128                             | 9.1        |
| Brass                        | 8.47           | 0.2                           | 97                              | 2.07       |
| SS 316                       | 8              | 0.29                          | 200                             | 1.45       |

2.3 Effect of flexure hinge geometry on compliance and stiffness

The compliance and stiffness of flexures varies from in-plane flexures to out-off plane flexure. Since the flexural diaphragm has out off- plane motion, so compliance and stiffness equations of out-off plane motion are considered [18]. Compliance and stiffness also varies from cross section of the flexures. Rectangular flexure with variable thickness, width, length is considered. Flexure is considered as cantilever beam subjected to an end loading. The out-off plane compliance formulation for rectangular flexural hinge can be calculated using equation (1):

$$C = \frac{4l^3}{Ew^3t}$$  \hspace{1cm} (1)

Where $l$ = Length of flexure, $t$ = Width of flexure, $w$ = Thickness of flexure, $E$ is Young’s modules of material. The stiffness of the flexure is reciprocal of the compliance. The compliance and stiffness of the cantilevered beam constructed of homogeneous metallic materials i.e. stainless steel, beryllium copper and brass. Two different thickness flexure hinges are considered to study their compliance and stiffness i.e. 100µm and 150µm. The length and width of flexures are varied and compliance and stiffness are calculated.

(a) Compliance at 1mm width 150µm

(b) Stiffness at 1mm width 150µm
Figure 1. Variation of compliance and stiffness of flexure hinges with respect to variable length, width and thickness

Compliance and stiffness of stainless steel, beryllium copper and brass flexure hinges is shown in Figure 1. The above figure 1 (a), (b), (c) and (d) shows the variation in the compliance and stiffness of flexure for 150µm thickness 1mm and 2mm width flexure hinge respectively. Figure 1 (e), (f), (g) and (h) shows the variation in the compliance and stiffness of flexure for 100µm thickness 1mm and 2mm width flexure hinge respectively. Maximum compliance is obtained for the brass flexure hinge can be
seen in figure 1 (a). From figure 1 (b) it can be seen that the stiffness of flexure hinges decreases as the length increases. Similarly in all other cases it can be observed that increase in the length of the flexures will increase the compliance of the flexures and decrease the stiffness of flexures. It is observed from the figure 1 that the compliance and stiffness value is varies for different material flexure. Maximum compliance is obtained for brass flexure compared to beryllium copper and stainless steel flexure hinge in all cases. The maximum deflection is obtained when the length of flexure is increases. It is also found that the maximum deflection can be is obtained from the thinner flexure hinge i.e. for 100µm because of higher compliance and low stiffness.

As the thickness increases the compliance of flexures decrease which will make the diaphragm stiffer. The length and the width of the flexures hinge for diaphragm are analyzed based on the compliance and stiffness of the flexure hinge. Higher the value of compliance will give more deflection. The number of flexures on the diaphragm will also affect the deflection of diaphragms. As the flexures numbers increases the deflection will decreases. More number of flexures on the diaphragms will make the diaphragm stiffer which leads to less deflection. Minimum three flexure hinges are needed to get sufficient deflection.

The flexures in this case are similar to the fixed beams. To make flexure diaphragm more flexible the effective length of the flexures has to be increased. Flexures in diaphragms have advantages because of its lower stiffness that cases mean higher value of deflection in diaphragm. And also these flexure diaphragms can easily design and fabricated. The diaphragm consists of 3 flexure hinges which are placed 120° apart. The parameters considered for three flexure hinge diaphragm simulations are given in the table 2.

| Flexure hinge diaphragm parameter |  |
|-----------------------------------|--|
| Diaphragm thickness              | 100 µm  |
| PVDF thickness                   | 52 µm   |
| PVDF diameter                    | 16 mm   |
| Outer diameter of diaphragm       | 21 mm   |
| Actuating area diameter          | 16 mm   |
| Width of flexure                  | 2 mm    |
| Length of flexure                 | 2 mm    |

### 3. Results and discussion

To evaluate the central deflection of the diaphragms, the simulation is carried out in COMSOL multiphysics software. PVDF actuator is used for diaphragm actuation. In the simulation the PVDF thickness and diameter is kept constant for all the diaphragms i.e. 52µm. The voltage is applied to the PVDF plate which is attached to the actuating area of the diaphragms. 90V to 140V driving voltage is applied to PVDF in steps of 10V. Simulation is carried out for all three different material i.e. stainless steel, beryllium copper, and brass flexure hinge diaphragm and compared with the different material plane diaphragms. The response of PVDF single layer film is designed modeled for plane and three flexure hinge diaphragms using COMSOL. The outer diameter of diaphragm is 21mm, actuating area is 16mm.
Figure 2. Mesh model and boundary conditions of (a) Plane diaphragm (b) Three flexure hinge diaphragm

The mesh model and boundary conditions considered for the simulation of plane diaphragm and three flexure hinge diaphragm are shown in figure 2 (a) and (b) respectively. The outer circumference of the diaphragm is considered as fixed constraint boundary condition. The diaphragm central deflection is measured at different voltage (i.e. 90V to 140V at step size 10V). Figure 3 (a) and (b) shows the central deflection 4.78µm and 12.10µm of plane diaphragm and three flexure hinge brass diaphragm at 140V.

Figure 3. Simulated deflection plot (a) Plane diaphragm (b) Three flexure hinge Brass diaphragm at 140V

Figure 4. Comparison of central deflection obtained for three flexure diaphragm with different materials at various voltages
It is observed from the figure 4 that the diaphragm material has strong influence on the central deflection of diaphragm. Brass diaphragm has much better deflection compared to stainless steel and beryllium copper because of its less Young’s modules and high resilience.

Figure 5 shows that the comparison of deflection of three flexure hinge diaphragm with plane diaphragm it is clear that the deflection of diaphragm increase linearly as the voltage increases. To verify the performance of the different material flexural hinge diaphragms, the voltage is applied across the PVDF. The present simulation results show that the central deflection of the three flexure diaphragms is twice that of the deflection of the plane diaphragm at same actuation voltage which is different for different materials. Based on the application we can select the diaphragm material. However the large deflection is obtained of brass in both plane and flexure hinge diaphragm because of less young’s modules. Compared to existing plane diaphragms, the diaphragm presented in this paper will not only increase the diaphragm deflection at same operating voltage, but also reduce the mass of diaphragm. Based on the application and requirements the diaphragm materials can be selected.

4. Conclusion

The performance of mechanical type of micropump is usually characterized by flow rate which mainly depends on diaphragm displacement. Compliant mechanism based flexure hinge diaphragms with different flexures geometry and materials have been simulated in this paper using COMSOL Multiphysics. Flexure hinge diaphragm is simple structure and more efficient compared to plane diaphragms. The effect of various design parameters of flexure hinges are thickness, width, length, Young’s modules on the compliance and stiffness of the diaphragm is studied. The simulation results show that the deflection of the flexural hinge diaphragm is approximately twice that of plane diaphragm, for the same actuation voltage. The effect of flexures dimension and material on the diaphragm deflection is studied and compared with plane diaphragm. The piezo actuated flexure hinge diaphragm is more effective with less mass and low power consumption compared to plane diaphragms. Simulation results show that the maximum deflection of 6.75µm 10.89µm 12.10µm is obtained for stainless steel, beryllium copper and brass diaphragm respectively with 2mm width and 2mm length flexure hinge at 140V.
References

[1] Huang, X., & Chuan, T. K. (2002). MEMS-micropumps: a review. In Journal of Fluids Engineering-Transactions of the ASME.
[2] Laser, D. J., & Santiago, J. G. (2004). A review of micropumps. Journal of micromechanics and micro engineering, 14(6), R35.
[3] Zengerle, R., Richter, A., & Sandmaier, H. (1992, February). A micro membrane pump with electrostatic actuation. In Micro Electro Mechanical Systems, 1992, MEMS'92, Proceedings. An Investigation of Micro Structures, Sensors, Actuators, Machines and Robot. IEEE (pp. 19-24). IEEE.
[4] Van Lintel, H. T. G., Van de Pol, F. C. M., & Bouwstra, S. (1988). A piezoelectric micropump based on micromachining of silicon. Sensors and actuators, 15(2), 153-167.
[5] Olsson, A., Enoksson, P., Stemme, G., & Stemme, E. (1997). Micromachined flat-walled valveless diffuser pumps. Journal of microelectromechanical systems, 6(2), 161-166.
[6] Zhang, W., & Ahn, C. H. (1996, June). A bi-directional magnetic micropump on a silicon wafer. In Solid-State Sensor and Actuator Workshop (pp. 94-97).
[7] Van de Pol, F. C. M., Van Lintel, H. T. G., Elwenspoek, M., & Fluitman, J. H. J. (1990). A thermopneumatic micropump based on micro-engineering techniques. Sensors and Actuators A: Physical, 21(1-3), 198-202.
[8] Benard, W. L., Kahn, H., Heuer, A. H., & Huff, M. A. (1998). Thin-film shape-memory alloy actuated micropumps. Journal of Microelectromechanical Systems, 7(2), 245-251.
[9] Woias, P. (2001, October). Micropumps--summarizing the first two decades. In Proc. SPIE (Vol. 4560, pp. 39-52).
[10] Smits, J. G. (1990). Piezoelectric micropump with three valves working peristaltically. Sensors and Actuators A: Physical, 21(1-3), 203-206.
[11] Olsson, A. (1998). Valve-less diffuser micropumps (Doctoral dissertation, School of Electrical Engineering, Royal Institute of Technology).
[12] Stemme, E., & Stemme, G. (1993). A valveless diffuser/nozzle-based fluid pump. Sensors and Actuators A: physical, 39(2), 159-167.
[13] Jeong, O. C., & Yang, S. S. (2000). Fabrication and test of a thermopneumatic micropump with a corrugated p+ diaphragm. Sensors and Actuators A: Physical, 83(1), 249-255.
[14] Junwu, K., Zhigang, Y., Taijiang, P., Guangming, C., & Boda, W. (2005). Design and test of a high-performance piezoelectic micropump for drug delivery. Sensors and Actuators A: Physical, 121(1), 156-161.
[15] Suzuki, T., Teramura, Y., Hata, H., Inokuma, K., Kanno, I., Iwata, H., & Kotera, H. (2007). Development of a micro biochip integrated traveling wave micropumps and surface plasmon resonance imaging sensors. Microsystem technologies, 13(8-10), 1391-1396.
[16] Zhan, C., Lo, T., Liu, L., & Peihsin, T. (1996). A silicon membrane micropump with integrated bimetallic actuator. Chinese journal of electronics, 5(2), 33.
[17] Lobontaia, N. (2002). Compliant mechanisms: design of flexure hinges. CRC press.
[18] Wu, L., Yuan, W., Hu, N., Wang, Z., Chen, C., Qiu, J & Li, Y. (2014). Improved piezoelectricity of PVDF-HFP/carbon black composite films. Journal of Physics D: Applied Physics, 47(13), 135302.
[19] MohdZubir, M. N., &Shirinzadeh, B. (2009). Development of a high precision flexure-based microgripper. Precision Engineering, 33(4), 362-370.