International Journal of Engineering & Technology, 7 (2.21) (2018) 66-71

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Design, fabrication and experimental studies of compliant flexure diaphragm for micro pump

R. Roopa[1*], P. Navin Karanth[2], S.M. Kulkarni[3]

[1]*Department of Mechanical Engineering, NITK, Surathkal, India.*
[2]*Department of Mechanical Engineering, NITK, Surathkal, India.*
[3]*Department of Mechanical Engineering, NITK, Surathkal, India.*
**Corresponding author E-mail:roopa.hassan89@gmail.com*

Abstract

This study reports the performance of piezo actuated compliant flexure diaphragm for micropump and MEMS application. To achieve the high performance of diaphragm at the low operating voltage compliant flexure diaphragm design is introduced. Very limited work has done on the diaphragms of micropump. Large numbers of mechanical micropumps have used plane diaphragms. The central deflection of diaphragm plays an important role in defining the micropump performance. The flow rate of mechanical type micropump strongly depends on the central deflection of diaphragm. In this paper compliant flexure diaphragms are designed for micropump to achieve higher deflection at lower operating voltage. Finite element analysis of compliant flexure diaphragm with single layer PVDF (Polyvinylidene fluoride) actuator is simulated in COMSOL. Compliant flexure diaphragms with a different number of flexures are analyzed. The central deflection of compliant flexure diaphragms is measured for driving voltages of 90V to 140V in 10 steps. The deflection of the compliant flexure diaphragm mainly depends on flexure width and length, the number of flexures in the diaphragm, PVDF thickness, diaphragm thickness and driving voltage. Use of compliant flexure diaphragm for micropump will reduce the mass and driving voltage of micropump. An attempt is made to compare the results of compliant flexure diaphragms with plane diaphragms. From the experimental results it is noticed that the compliant flexure diaphragm deflection is twice that of the plane diaphragm at same driving voltage. Deflection of three flexure and four flexure compliant diaphragms is 10.5µm and 11.5µm respectively at 140V.

Keywords: *Compliant, out-of-plane, PVDF (Polyvinylidene fluoride), flexure, micro pump.*

1. Introduction

In the recent years microfluidic system has been the focus of some researcher, which supports mainly in the field of medical, biomedical applications such as injection of glucose, insulin, cardiology systems, blood transportation, biological analysis etc. Some of other application of micropumps in micro cooling system, fuel injection, propelling micro-spacecrafts. In these entire applications micropump is one of basic component of the microfluidic system. Use of high operating voltage micropumps for medical and biomedical applications may change the property of liquid which is present inside the micropump. Hence there is a high need for low operating voltage, less mass, high accuracy and reliable micropumps for medical and bio-medical application. In general, micropumps are classified into two type's mechanical and non-mechanical types of micropump (Nisar et al. 2008). The diaphragm micropump which comes under mechanical pump with active valve has are more efficient, free from valve clogging, wear and fatigue. The diaphragms of micropump is actuated using various actuation principle such as electrostatic (Bourouina et al. 1997), electromagnetic (Bohm et al. 1999), thermo pneumatic (Van at al. 1990), Piezoelectric (Carrozza et al. 1995), shape memory alloy (Makino et al. 2001) etc. Piezoelectric actuation is most popular and commonly used earliest mechanism type of actuation for micropumps. This is because of fast mechanical response, high stroke volume, good reliability, energy efficiency, low power consumption and high actuating force (Woias et al. 2001). Some of the materials used for actuation in piezo actuated micropump PVDF (Polyvinylidene difluoride and PZT (Lead zirconate titanate), since PZT being a ceramic is brittle in nature, poses problem for deposition and environmental hazardous element lead (Wang et al. 2014). PVDF is the commercially available piezoelectric polymer in the form of thin films of thickness ranging from 10 to 760µm.

The diaphragm type micropump has two mode of operation i.e. suction mode and pumping mode. In suction mode diaphragm deflects up wards which results in negative pressure in pump chamber due to this more fluid enters the chamber through inlet valve. In case of pumping mode diaphragm moves downward this creates positive pressure inside chamber which causes more fluid to leave the chamber through outlet valve. When the electric field is applied to the diaphragm of the micropump the diaphragm expand or contract which leads to the net flow of liquid from inlet to outlet through diffuser/nozzle as shown in Fig.1.

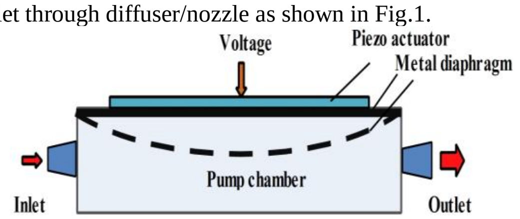

Fig.1. Schematic of mechanical type diaphragm micropump

The performance of the mechanical type micropump depends on the diaphragm deflection. Many researchers have attempted to improve pump performance by modifying diaphragms and diaphragm numbers. P+ silicon electrostatic actuated corrugated diaphragm for micropumps are fabricated and tested to eliminate the residual stress in diaphragms and to increase the diaphragm deflection (Yang et al. 1995). Later thermo pneumatic actuated P+ silicon corrugated diaphragm for valveless micropumps is introduced (Jeong et al. 2000). Silicon corrugated diaphragm for MEMS application is developed (Soin et al. 2006). The design and fabrication of corrugated diaphragms are difficult compared to plane diaphragms and these corrugated diaphragms are not suitable for all actuating principle micropumps (Yang et al. 1995). The only solution to increase the deflection in the plane diaphragm is to change the operating frequency and mode of vibration (Teymoori et al. 2002). Less deflection of diaphragm will leads to decrees flow rate of micropump (Singh et al. 2015). Our main aim is to increase the deflection of diaphragm which in case leads to maximum flow rate. Less work has done on the performance improvement of diaphragms through modifying of diaphragm design. In this investigation, we propose a compliant flexure diaphragm for the mechanical type micropump.

Compliant mechanisms provide guided motion via elastic deformation. Their ability to produce repeatable/precise frictionless motion makes them a common choice in precision positioning devices, frictionless bearings, biomedical devices and robotic (Lobontiu, N. 2002). Compliance in design leads to joint less, no-assembly, monolithic mechanical devices and is particularly suited for application with small range of motions (Kota et al. 2001). 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 (Howell 2013). Flexures in diaphragm are mainly used to provide out-of-plane motion in MEMS devices, actuators, sensors, flow control, frictionless linear bearing (Awtar et al. 2005). Flexure hinge produces relative motion/rotation between two adjacent rigid members through bending (Lobontiu, N. 2002). Mechanisms which are based on flexural hinges are also a beneficiary in biomedical industry for biomedical devices like biopsy devices, orthotic devices, vascular catheters etc. Flexure based mechanism such as diaphragm flexure involves the load suspended on the radial and tangential arrangement of flexure beams. The diaphragm flexures with central rigid mass with connected by three small flexure lengths are modeled which are applicable in telecommunication mirrors (Shilpiekandula et al. 2010). Rectangular cross section flexures are most suitable for out-of-plane motion (Lobontiu 2002). Materials with high resilience are able to withstand larger deflection, brass diaphragm is selected as diaphragm material based on the resilience property (MohdZubir et al. 2009).

Flexures on diaphragm are commonly used to provide precise out of plane motion in various applications such as voice coil actuators, pressure sensors, flow-control, flexible coupling, MEMS devices and frictionless bearings (Awtar et al. 2005). The design of diaphragm plays a very important role as it defines the performance if micropump to generate maxiumu deflection. In this paper compliant flexural diaphragms are designed and results are presented. These compliant flexure diaphragms will reduce the actuation voltage and mass of diaphragm, increase the central deflection which leads to increase micropump performance.

2. Simplified analytical model of flexure diaphragm

Geometrical design of diaphragm plays an important role in achieving higher performance of diaphragm at lower operating voltage. Flexures in the diaphragm are commonly used for providing motion in the direction normal to the flexure plane i.e. out-of-plane motion. The active and resistive loads are in planar in case of in-plane flexures application where as in case of out-of-plane flexure application the loads are in the perpendicular direction (Lobontiu 2002).

The flexural diaphragm has out-of-plane motion so rectangular flexures are more suitable for this application. To make flexure diaphragm more flexible the effective length of the flexures has to be increased (Lobontiu 2002). Flexuresin diaphragm are considered as cantilever beam subjected to an end loading (Hai-Jan et al. 2012). The length and the width of the flexures are analyzed based on the compliance and stiffness of the flexure beam. Lower the value of stiffness will give more deflection. The flexures act as fixed guided beams, the stiffness of flexure is given in equation (1)

$$k = \frac{E*t*w^3}{L^3} \tag{1}$$

Where w is the width of the flexures, L is the length of the flexures, t is the thickness of flexure and E is young's modules. The stiffness of the diaphragm mainly depends on material properties, diaphragm thickness, flexure length and width and the number of flexures in the diaphragm. The main objective in the case of flexural in the diaphragm is to maximize the deflection in the desired direction (i.e. to maximize the out of plane motion). A rectangular cantilevered beam with the homogeneous brass material is considered for the diaphragm. 100μm thickness flexure with 2mm width and 2mm length is considered for flexure diaphragm design.

The design based on compliant mechanism and consisting of flexures is solved on the basis of force-deflection. In this the voltage given to piezoelectric layer is converted to force acting on diaphragm by Pin force model. The pin force model of Crawley and de Luis assumes that deformation is transferred from the piezo to the diaphragm through actuation forces concentrated at the ends of the actuator patch (Deshpande et al. 2007). Thus actuator is modelled as beam with only axial stiffness. Since the thickness of diaphragm is less compared to cross section dimensions, this model is used for this purpose. According to pin force model, the force is given in equation (2).

$$\mathrm{F} = \frac{\mathrm{V\,A_d Ed_{31}}}{\mathrm{t_P}} \tag{2}$$

Where, V is applied voltage, Ad cross section area of the diaphragm, E is young's modules of the piezoelectric actuator, d_{31} is piezoelectric strain constant for PVDF and tp is the thickness of piezoelectric actuator which is attached to the middle part of the diaphragm.The force on the diaphragm due to applied electrical voltage to piezo actuator. Fig.2 shows the schematic of compliant flexural diaphragm. The design parameters of the compliant flexure diaphragm are listed in Table 1 based on the stiffness value.

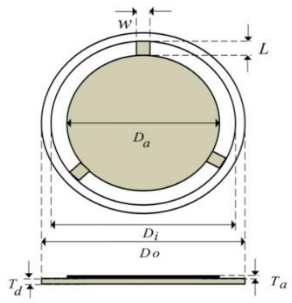

Fig.2. Schematic representation of flexural diaphragm

Table 1: Parameters of diaphragm and actuator

Parameter	Symbol	Flexural diaphragm	Plane diaphragm
Outer diameter	D_o	21mm	21mm
Actuation area diameter	D_a	16mm	16mm
Diaphragm thickness	T_d	100μm	100μm
Actuator thickness	T_a	52μm	52μm
Inner diameter	D_i	18mm	-
Width of flexure	W	1.5mm	-
Length of flexure	L	2mm	-

The number of supporting flexures in the diaphragms is varied from two to four which are placed at an equal distance. Side view of the flexural diaphragm is as shown in Fig.3 (a) where flexures are represented as springs. Fig.3 (b) shows two flexure diaphragm where flexures are placed at180^0 apart. Fig.3 (c) and (d) shows the three flexures diaphragm and four flexure diaphragm where flexures are placed at120^0 and 90^0 respectively. Effect of increase in the number of flexures in diaphragm will be studied and compared later.

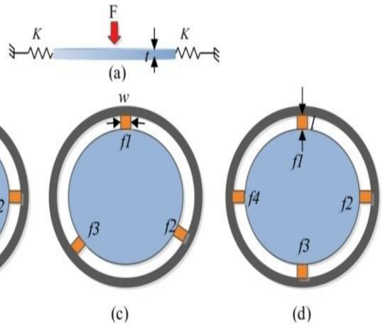

Fig.3 (a) Side view of flexure diaphragm and top view of (b) Two flexure diaphragm (c) Three flexure diaphragm (d) Four flexure diaphragm

The compliant flexure diaphragm can be represented as uniformly loaded circular plate supported by elastic springs (Qian et al 2002). The flexures which are connected to the diaphragms are considered as springs in parallel combination with middle mass. Each of the individual flexures (springs) supports the deflection area of the diaphragm. Each flexure undergoes the same deflection when the force is applied to the diaphragm through PVDF. Since flexures/springs are considered as a parallel combination the equivalent stiffness of flexure is sum of individual stiffness of each flexure. Force acting on the diaphragm is calculated based on Pin force model equation (2). Equivalent spring constant is the sum of the stiffness of each spring which are connected in parallel with the diaphragm. Since the stiffness of each spring is same, K_{equ}=nK where n is number of flexures attached to the diaphragm. Deflection of the diaphragm is thus calculated by equation (3).

$$X = \frac{F}{K_{equ}} \qquad (3)$$

3. FE model of flexural diaphragm

FE software package COMSOL is used to determine the central deflection of compliant flexure diaphragm. The details of materials and elements used for FE modeling of diaphragm are given in Table 2. The interface between metal diaphragm and PVDF are glued. The edges of the brass compliant flexure diaphragm and plane diaphragm have fixed and zero-displacement boundary conditions are applied. The voltage of 90 to 140V in 10 step size is applied to the PVDF for actuation. The effect of increase in the number of flexure in compliant diaphragms is studied and compared with plane diaphragm.

Table 2: Diaphragm Modeling Details

Part	Material	E (GPa)	**Element type**	Poisson's Ratio
Actuator	PVDF	8.3	**Solid 226**	0.18
Metal diaphragm	Brass	97	**Solid 186**	0.33

E=Young's Modules

PVDF films of 52µm thickness are considered for diaphragm actuation. The PVDF film bottom surface of is kept at zero potential to represent the ground electrode of the film. The voltage is applied to the top surface of the PVDF. When the voltage is applied to the PVDF it is assumed that the diaphragm undergoes uniform loading. The COMSOL meshed model of three flexure compliant diaphragm is shown in Fig.4.

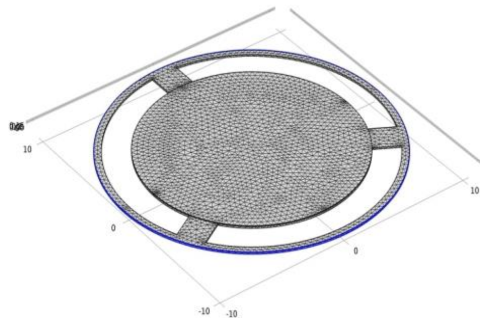

Fig.4 Mesh model of three flexure compliant diaphragm

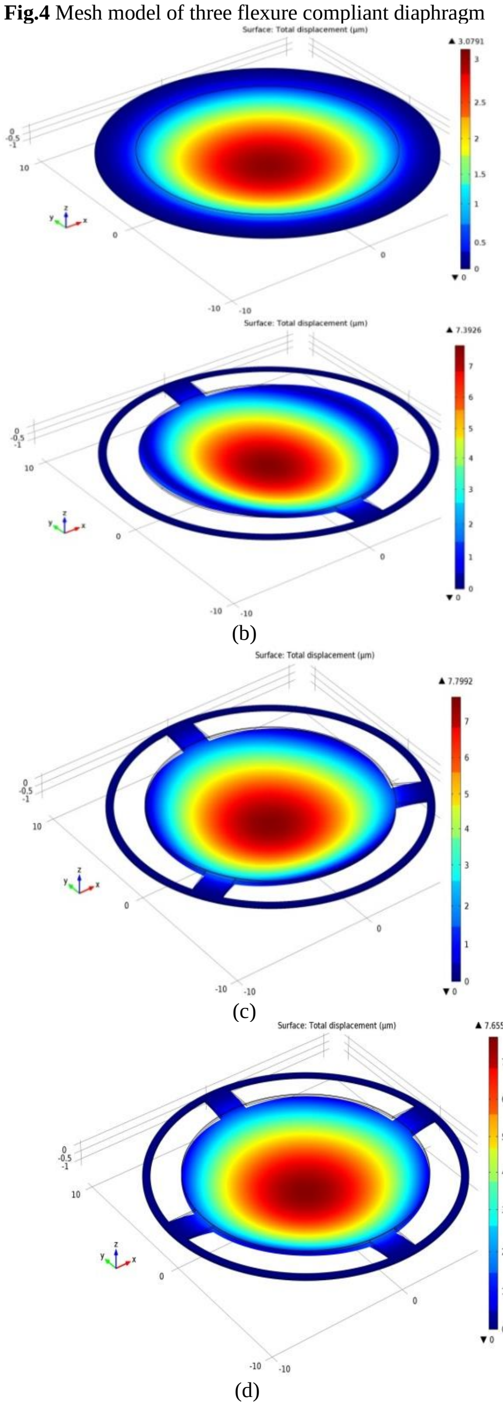

Fig.5. Displacement plot (a) Plane diaphragm (b) Two flexure compliant diaphragm (c) Three flexure compliant diaphragm (d) Four flexure compliant diaphragm

The model analysis is performed to determine the natural frequency. The frequencies corresponding to plane diaphragm, two flexure diaphragms, three flexure diaphragms and four flexure diaphragms are 2241 Hz, 1923 Hz, 1987 Hz and 2101 Hz respectively. The central deflection of the plane diaphragm is 1.74

µm at 90V is shown in Fig.5 (a). The displacement plot of the two flexure diaphragms is shown in Fig.5 (b).The central deflection of two flexure diaphragm at 90V is 3.18µm. Displacement plot of three and four flexure diaphragm is 3.34µm and 3.34µm at 90V is shown in Fig.5 (c) and (d) respectively. The central deflection of the plane and different flexure diaphragms at 90-140V in steps of 10V are studied. From Fig.8 shows the FE result of plane diaphragm and flexure diaphragm and it is observed that flexure diaphragms deflection is much higher (>48%) compared to the plane diaphragm. Even though the diaphragm having two flexures has better displacement in FE and analytical results than three flexures diaphragm it cannot be used because of twisting action and negative deflection. The maximum deflection is obtained from the three and four flexure diaphragms compared to other flexure diaphragms at same actuation voltage, for further study three and four compliant flexure diaphragms are considered. From the FE results it can observe that increase in the number of flexures in diaphragm will give less deflection due to increase in the stiffness of diaphragm.

4. Experimental setup

The deflection of the compliant flexure diaphragm is measured using leaser pickup setup. The flexural diaphragms are machined using Fanuc Robocut c400iA Wire EDM. Electrically conductive adhesive transfer tape is used to glue the PVDF on the brass metal diaphragm. The electric field is applied across the PVDF film. The diaphragm central deflection is observed and measured using laser pickup (opto NCDT-1402) and NI 9264 data acquisition hardware is used to acquire the data through Lab VIEW software. The sinusoidal voltage signal is generated from function generator and amplified by passing through driver circuit, then that voltage is applied to the PVDF actuator. The displacement is measure for voltage of 90 to 140V for step size of 10V. Fig.6 Illustrate the experiment setup to measure the deflection of the diaphragm. The diaphragm is actuated at nearest frequencies obtained from FE results. Frequency sweeping is conducted to determine the frequency at which maximum deflection is achieved. The diaphragm is fixed to the acrylic supporting base. Input voltage is applied to the diaphragm using signal generator and driver circuit. The displacement of diaphragm is experimentally acquired by laser pickup and stored by increasing the driving voltage in steps of 10V from ±90V to maximum ±140V.

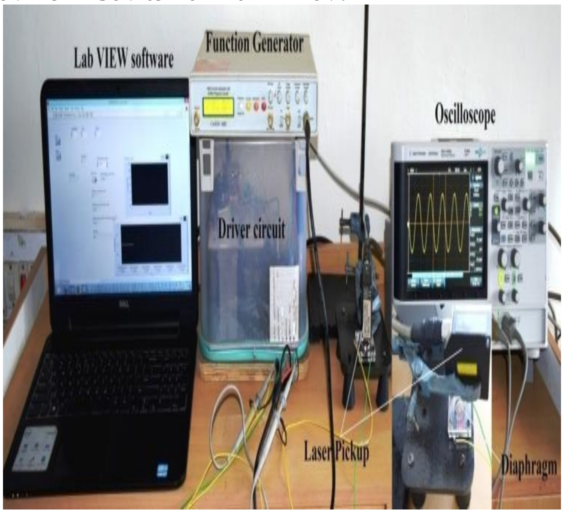

Fig.6. Experimental setup to measure central deflection

5. Result and discussion

The effects of number of flexures in diaphragm are studied at different operating voltage. The peak-to-peak voltage of 90Vto 140V are considered. The validations of experimental results are compared with FE simulation and simplified analytical results.

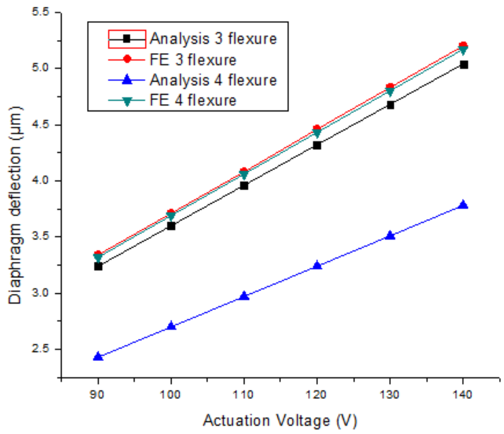

Fig.7. Deflection versus driving voltage of three and four flexure diaphragm: comparison of analytical and FE results.

Fig.7 shows the comparison of analytical and FE results of three and four flexure diaphragm. Effective way to verify the analytical solution is to compare it with FE results. It is observed that deflection of diaphragm increases with increase linearly in input voltage in both cases. It is observed that maximum deflection is obtained for three flexure diaphragm in analytical and FE results. Also, it is observed that increase in the number of flexures in diaphragm will reduce the deflection, this is due to increase in the stiffness of the diaphragm. The FE simulation has maximum central deflection for three flexure diaphragm compared to analytical determined one. The maximum deflection obtained from analytical result of three flexure diaphragm is 3.24µm and deflection from FE simulation is 3.34µm, resulting in less discrepancy. This may be due to some reasons like the glue between metal diaphragm and PVDF is not considered in analytical result.

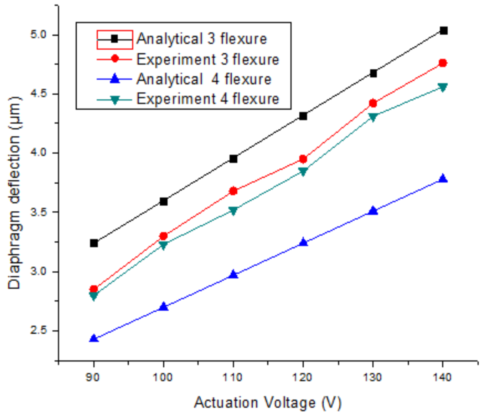

Fig.8. Deflection versus driving voltage of three and four flexure diaphragm: comparison of analytical and experimental results

Fig.8 shows comparison of analytical and experimental result of three and four flexure diaphragm. The deflection of diaphragm increased linearly with increase in the applied voltage in both the case. The relation between the actuation voltage and actual force is calculated using pin force model, which is beyond the scope of this paper. The simplified present analytical model was applied to predict the central deflection of flexural diaphragm. There is a close agreement between the analytical model and experimental results although glue is not considered in analytical model.

The effect of input voltage on the diaphragm is studied experimentally and results are compared with obtained from FE results are shown in Fig.9. From the experiment the maximum displacement of three flexure diaphragm is 4.7µm at 140V. The FE results have maximum central deflection compared to experimental one. This may be due to some reasons like error in fabrication of flexural diaphragm.

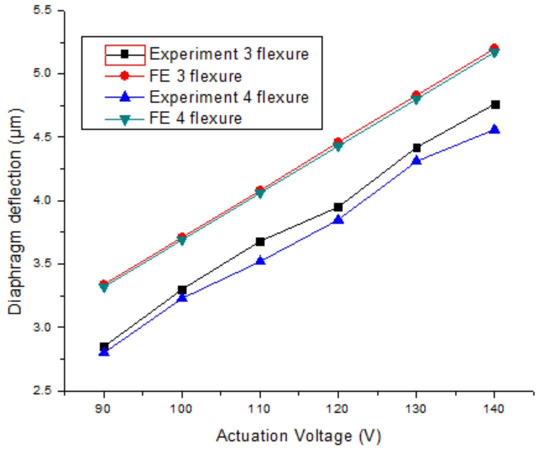

Fig.9. Deflection versus driving voltage of three and four flexure diaphragm: comparison of experimental and FE results

Where as in case of FE result the bonding material between metal diaphragm and piezo actuator is not considered. There may be slight variation in fixing boundaries of diaphragm in experiment. From the analytical, FE simulation and experimental results, it is confirmed that the deflection of compliant flexure diaphragm is twice that of the plane diaphragm. All results shows that deflection of the diaphragm increases linearly with applied input voltage. The experimental results are approximately agreeing with the FE simulation and analytical result.

6. Conclusion

This study proposes a piezo-actuated compliant flexure diaphragm for micropumps application. COMSOL modeling of compliant flexure diaphragm with single layer PVDF is studied. The compliant flexure diaphragms have been fabricated and the deflection of the diaphragms has been experimentally measured using laser pickup. The experimental data agreed well with simplified analytical model and FE results. Moreover, the best flexure diaphragm among different flexure diaphragm was examined. The central deflection of the three flexure compliant diaphragm is twice that of the plane diaphragm at the same input voltage, this indicates that the power consumption of compliant flexure diaphragm is less. It was found that as number of flexures in compliant diaphragm increases i.e. more than three flexures will decrease the central deflection of diaphragm. This is due to increase in the stiffness of the flexure in the diaphragm. The analytical, FE result and experimental illustrates that the compliant flexure diaphragm is effective and preferable to use in piezo-actuated micropump application and other MEMS applications. Piezo-actuated flexure diaphragm valveless micropump will be characterized in future to justify compliant flexure diaphragm.

References

[1] Awtar S & Slocum AH, *Flexure systems based on a symmetric diaphragm flexure*. ASPE1803, (2005).

[2] Azarbadegan A, Cortes-Quiroz CA, Eames I & Zangeneh M, "Analysis of double-chamber parallel valveless micropumps", *Microfluidics and Nanofluidics*, Vol.9, No.2-3, (2010), pp.171-180.

[3] Bourouina T, Bossebuf A & Grandchamp JP, "Design and simulation of an electrostatic micropump for drug-delivery applications", *Journal of Micromechanics and Micro engineering*, Vol.7, No.3, (1997).

[4] Böhm S, Olthuis W & Bergveld, P, "A plastic micropump constructed with conventional techniques and materials", *Sensors and Actuators A: Physical*, Vol.77, No.3, (1999), 223-228.

[5] Carrozza MC, Croce N, Magnani B & Dario P, "A piezoelectric-driven stereo lithography-fabricated micro pump", *Journal of Micromechanics and Micro engineering*, Vol.5, No.2, (1995).

[6] Deshpande M & Saggere L, "An analytical model and working equations for static deflections of a circular multi-layered diaphragm-type piezoelectric actuator", *Sensors and Actuators A: Physical*, Vol.136, No.2, (2007), pp.673-689.

[7] Huang CW, Huang SB & Lee GB, "Pneumatic micro pumps with serially connected actuation chambers", *Journal of micromechanics and micro engineering*, Vol.16, No.11, (2006).

[8] Kan J, Tang K, Liu G, Zhu G & Shao C, "Development of serial-connection piezoelectric pumps", *Sensors and Actuators A: Physical*, Vol.144, No.2, (2008), pp.321-327.

[9] Kota S, Joo J, Li Z, Rodgers SM & Sniegowski J, "Design of compliant mechanisms: applications to MEMS", *Analog integrated circuits and signal processing*, Vol.29, No.1-2, (2001), pp.7-15.

[10] Jeong OC & Yang SS, "Fabrication and test of a thermo pneumatic micropump with a corrugated p+ diaphragm", *Sensors and Actuators A: Physical*, Vol.83, No.1, (2000), pp.249-255.

[11] Howell, L. L., Magleby, S. P., & Olsen, B. M. (Eds.). (2013). *Handbook of compliant mechanisms*. John Wiley & Sons.

[12] Kota S, Joo J, Li Z, Rodgers SM & Sniegowski J, "Design of compliant mechanisms: applications to MEMS", *Analog integrated circuits and signal processing*, Vol.29, No.1-2, (2001), pp.7-15.

[13] Lobontiu N, "Out-of-Plane (Diaphragm) Compliances of Circular-Axis Notch Flexible Hinges with Midpoint Radial Symmetry", *Mechanics Based Design of Structures and Machines*, Vol.42, No.4, (2014), pp.518-538.

[14] Lobontiu N, *Compliant mechanisms: design of flexure hinges*. CRC press, (2002).

[15] Makino E, Mitsuya T & Shibata T, "Fabrication of TiNi shape memory micro pump", *Sensors and Actuators A: Physical*, Vol.88, No.3, (2001), pp.256-262.

[16] MohdZubir MN & Shirinzadeh B, "Development of a high precision flexure-based micro gripper", *Precision Engineering*, Vol.33, No.4, (2009), pp.362-370.

[17] Nisar A, Afzulpurkar N, Mahaisavariya, B & Tuantranont, A, "MEMS-based micro pumps in drug delivery and biomedical applications", *Sensors and Actuators B: Chemical*, Vol.130, No.2, (2008), pp.917-942.

[18] Olsson A, *Valve-less diffuser micro pumps* (Doctoral dissertation, School of Electrical Engineering, Royal Institute of Technology), (1998).

[19] Peng TJ, Yang ZG, Cheng GM, Kan JW & Zeng P, "Design of double-chamber piezoelectric pump [J]", *Optics and Precision Engineering*, (2009).

[20] Qian J & Zhao, YP, "Materials selection in mechanical design for micro sensors and micro actuators", *Materials & design*, Vol.23, No.7, (2002), 619-625.

[21] Stemme E & Stemme G, "A valveless diffuser/nozzle-based fluid pump", *Sensors and Actuators A: physical*, Vol.39, No.2, (1993), pp.159-167.

[22] Soin N & Majlis B, "Development of perfect silicon corrugated diaphragm using anisotropic etching", *Microelectronic engineering*, Vol.83, No.4, (2006), pp.1438-1441.

[23] Smits JG, *U.S. Patent No. 4,938,742*. Washington, DC: U.S. Patent and Trademark Office, (1990).

[24] Su HJ, Shi H & Yu J, "A symbolic formulation for analytical compliance analysis and synthesis of flexure mechanisms", *Journal of Mechanical Design*, Vol.134, No.5, (2012).

[25] Shilpiekandula V & Youcef-Toumi K, *Dynamic Modeling and Performance Trade-offs in Flexure-based Positioning and Alignment Systems*. INTECH Open Access Publisher, (2010).

[26] Singh S, Kumar N, George D & Sen AK, "Analytical modeling, simulations and experimental studies of a PZT actuated planar valveless PDMS micropump", *Sensors and Actuators A: Physical*, Vol.225, (2015), pp.81-94.

[27] Teymoori MM & Abbaspour-Sani E, "Design and simulation of a novel electrostatic peristaltic micro machined pump for drug delivery applications", *Sensors and Actuators A: Physical*, Vol.117, No.2, (2005), pp.222-229.

[28] Teymoori MM & Abbaspour-Sani EA, "A novel electrostatic micromachined pump for drug delivery systems", *IEEE International Conference on Semiconductor Electronics*, (2002), pp.105-109.

[29] Ullmann A, "The piezoelectric valve-less pump—performance enhancement analysis", *Sensors and Actuators A: Physical*, Vol.69, No.1, (1998), pp.97-105.

[30] Van de Pol FCM, Van Lintel HTG, Elwenspoek M & Fluitman JHJ, "A thermo pneumatic micro pump based on micro-engineering techniques", *Sensors and Actuators A: Physical*, Vol.21, no.1-3, (1990), pp.198-202.

[31] Wu L, Yuan W, Hu N, Wang Z, Chen C, Qiu J & Li Y, "Improved piezoelectricity of PVDF-HFP/carbon black composite films",

Journal of Physics D: Applied Physics, Vol.47, No.13, (2014), pp.135-302.

[32] Woias P, “Micropumps-summarizing the first two decades”, In *Proc. SPIE*, Vol.4560, (2001), pp.39-52.

[33] Yang EH, Yang SS, Han SW & Kim SY, “Fabrication and dynamic testing of electrostatic actuators with p+ silicon diaphragms”, *Sensors and Actuators A: Physical*, Vol.50, No.1, (1995), pp.151-156.

[34] Yamahata C, Lotto C, Al-Assaf E & Gijs MAM, “A PMMA valve less micro pump using electromagnetic actuation”, *Microfluidics and Nano fluidics*, Vol.1, No.3, (2005), pp.197-207.