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Modeling and Analysis of Check Valve Micro pump with Piezoelectrically Actuated Diaphragm

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***Abstract*— In the present technological enhancement and advancement, micro pumps are use to handle small and precise volumes of liquid for chemical, medical, biomedical and other fluidic controll activity in manufaturing system.The present paper is focused on the modeling and analysis of a piezoelectrically actuated check valve diaphragm of a micro pump for micro fluidic applications. In this paper, the present work is an attempt to investigate the mechanical behavior of a rectangular piezoelectrically actuated diaphragm for check valve micro pump. The main goal is to characterize the flow rate as function of diaphragm average displacement by considering the effect of other parameter such as voltage, frequency and backpressure in analyzing a piezoelectrically actuated diaphragm. Modeling and simulation of diaphragm plates is performed with a Finite Element Analysis (FEA) ANSYS software.**

***Index Terms*— Average diaphragm displacement, Finite Element Analysis (FEA) ANSYS, Micro pump, Piezoelectrically actuated Diaphragm.**

I. INTRODUCTION

Micro pump is a micro-scale device used for moving liquids or gases. It named as micro pump because it have length scales in the order of 100s µm or less. It mainly consists of a piezoelectric actuator glued in a silicon plate with the help of epoxy material, inlet chamber, one inlet and one outlet check valve. The voltage source is connected between the pump diaphragm and piezoelectric plate because piezoelectric material has electromechanical interaction between its mechanical and electrical state. When a piezoelectric material is subject to electrical field, it will change its dimension (compression and expansion in material take place). As device is connected with voltage source, the piezoelectric plate undergoes a successively compression and expansion .As piezoelectric plate is mounted on pump diaphragm (glued with conductive epoxy layer), Pump diaphragm also start vibrating along with piezoelectric plate. As the PZT plate undergoes on expansion, due to increase in volume pump chamber the pressure inside the chamber decreases and suction is created inside the chamber. Due to decrease in chamber pressure, the inlet valve open and fluid is flow inside the chamber. When PZT plate undergoes on compression, due to reduction in the volume of pump chamber the pressure inside the chamber increases and compression is take place inside the chamber. Due to this outlet valve of micro pump get open and fluid is delivered from the outlet port.

II. REVIEW

Micro pump is micro-scale device used for moving liquids or gases. Features of the pump have length scales in the order of 100s µm or less. The research on micro pump started on mid of 1970's. The first paper of micro pump published and fabricated on 1978 [1]. In this paper, the pump diaphragm and passive valves both are made from piezoelectric material. In design Consideration, the actuation is provided on both elements (in diaphragm and passive valves) [2]. This micro pump has maximum stroke volume of 1.94 µl with a pumping actuation voltage of 100V and output pressure of 100 mmHg. In this pumping volume and pressure as a function of voltage are calculated and experimentally verified [1], [2]. Since valve and body both are made of piezoelectric material so there may always chance for electrical short circuit. This problem is short out by replacing piezoelectric valves and body by silicon-based valves and body structure [3]. Further micro pump is design for bidirectional flow and

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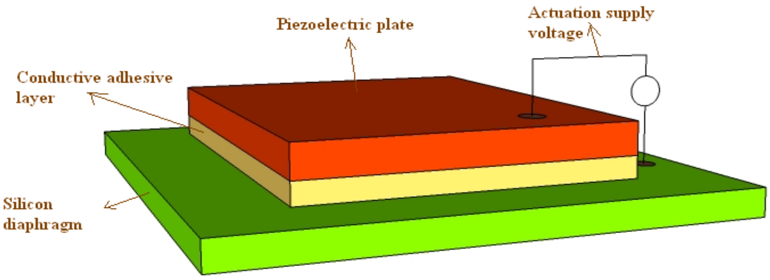

Fig-1 Schematic view of piezoelectric ally actuated diaphragm

passive valve is replace by active micro valve [6]. The integration of micro sensors and micro flow devices with the micro pump is done [3], [4]. To reduce the complexity of valve design, valve less micro pump with nozzle and diffuser is introduced [5], [13], [15]. The valve less micro pump has limitation of backflow and random flow. Due to these limitations precise control of pumping rate became difficult. So check valve micro pumps are preferred over valve less micro pumps because they have better performance and provide a better linearly controllable pumping rate range [8], [13], [15]. The pump flow linearly decreases with the increase of the pump pressure at a fixed excitation voltage [8], [9]. The maximum pump flow is linearly proportional to the excitation voltage. There is an optimal piezoelectric layer thickness for a high pump flow and thinner pump diaphragm would be helpful to improve the pump flow [9]. It is found that the PZT-5A actuator generates the largest pump flow among the three most commonly used piezoelectric materials [9]. The deflection of the piezoelectric actuator is increases with increase in the excitation voltage [10]. There is an optimal thickness ratio of the piezoelectric layer and the passive plate under the constant electric field for the large deflection [10]. The passive plate deflection decreases as the PZT thickness and bonding material thickness increases and increases as the PZT radius increases. For a constant electric field, there exists an optimal PZT thickness. When the bonding layer thickness increases, this optimal PZT thickness also increases [11]. Higher diaphragm Young's Modulus also improves the stroke volume if the diaphragm can be made thinner [11]. Micro pumps are mainly use to handle small and precise volumes of liquid for chemical, medical, biomedical and other fluidic controll activity in manufaturing system[9], [12], [14], [16].

III. MODELING OF MICRO PUMP AND DIAPHRAGM

To enhance performance, reduce complexity of micro fabrication, and save process cost, a check valve diaphragm micro pump actuated by piezoelectric mechanism was developed [8]. Parts of such pumps are micro machined using photolithography and etching, injection molding, precision machining. The main components of micro pump are an inlet check valve, an outlet check valve, a diaphragm, and a pump chamber. The micro pump structure was made from a triple wafer stack, two silicon-on-insulator (SOI) wafers and one silicon wafer as shown in figure-1.The movable part of device such as check valve and diaphragm are made from device layers of SOI wafers. Photolithography technique is used to fabricate the micro parts of device because it facilitates the better and precise control while working with small dimension. A check valve diaphragm micro pump having dimension of 14.5mm×9mm×1.1mm was fabricated with the micro fabrication processes [8]. PZT-5A plate (4mm×4mm×127µm) was manually coated on a thin conductive epoxy layer EPO-TEK H31 (4mm×4mm×20µm) and then the PZT plate was manually mounted to the center of the 5mm×5mm×40µm silicon diaphragm as shown in figure-1. The model of piezoelectrically actuated micro pump is shown in figure-2.

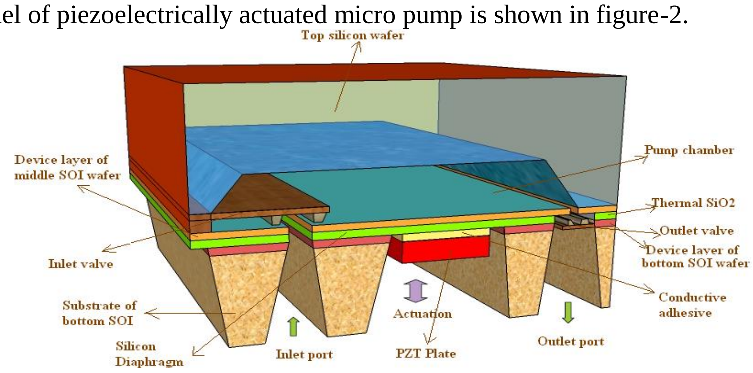

Fig-2. Cross sectional view of a check valve micro pump

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IV. WORK METHODOLOGY

In this instead of centre displacement, average displacement is taken as a design parameter because the center displacement is a discrete data point but average displacement gives the statistical data of a diaphragm. Since average displacement gives the statistical data point, so it can directly relates stroke volume of diaphragm and actuation voltage. During analysis we assume that both inlet and outlet check valve work perfectly. During working outlet check valve exert a back pressure on pump chamber as the inlet check valve remains closed. This back pressure equally distributed throughout the pump chamber including diaphragm as pump chamber is filled with the fluid. With the same actuation, if the pumping rate is proportional to actuation frequency in a certain frequency range, the pumping rate of a micro pump with a variable backpressure P at its outlet can be find out from the following equation[7]:

$$R(P, U) = f \cdot \Delta V(P, U) = f \cdot 2Dave(P, U) \qquad (1)$$

Where-R(P,U) is the pumping rate,
V(P,U) is the stroke volume of the diaphragm
f is the actuation frequency,
Dave (P,U) is diaphragm average
Displacement under a backpressure P and an
Actuation voltage U.

By Using Eq. (1), pumping rate R(P,U) can be calculated from a known average displacement Dave(P,U) and vice versa. If the actuation voltage is fixed (U=U0), as well as the relationship between the backpressure P and the corresponding average displacement Dave(P,U0is known , than we can determine the relationship between the backpressure P and the pumping rate R(P,U0).

For a fixed actuation voltage two extreme cases are possible

(1) For no backpressure P=0, the pumping rate is maximum or R max = R(0,U0).

(2) For certain threshold backpressure PT, the pumping rate becomes zero. as Pmax = PT, which corresponds to ΔV(PT,U0)=0 or Dave(PT,U0)=0.

With the same actuation voltage U0, the average displacement Dave(P,U0) under a biased backpressure P can be obtained in the following equation:

$$Dave(P, U0) = \frac{\iint_s z(x,y,P,U0)\,dx\,dy}{\iint_s dx\,dy} \qquad (2)$$

Where-z(x, y, P,U0) represents diaphragm point displacement at the location (x, y) with a biased pressure P and actuated by voltage U0, and S is the area of the silicon diaphragm.

By using equation (2), it is feasible to find the relationship between the backpressure P and silicon diaphragm average displacement Dave, since each backpressure P corresponding to a unique Dave. But due different type of material such as PZT-5A plate, thin conductive epoxy layer EPO-TEK H31 and silicon diaphragm is used so it became difficult to calculate Dave (P, U0) mathematically. So we use software capabilities to solve this problem.

V. SIMULATION AND ANALYSIS

Modeling of piezoelectric diaphragm is perform in a Finite Element Analysis (FEA) software ANSYS. Model consist of three rectangular plate, lower plate is of silicon diaphragm (5mm×5mm×40µm), middle plate is of thin conductive epoxy layer EPO-TEK H31 (4mm×4mm×20µm) and the upper plate is made of PZT-5A (5mm×5mm×40µm) as shown in figure-2. A uniform pressure P is applied on silicon diaphragm and actuation voltage is applied between the upper PZT-5A plate and silicon diaphragm with help of electrode as shown in figure-2.The electromagnetic couple field element Solid-226 with 20 nodes is chosen to model the piezoelectric layer. The 20-node solid 186 is used to model the model the bonding layer and couple field Solid 98 is use for passive plate. It is assume that residual stress and losses are zero within the whole structure. The meshing of whole structure is performing with free tetrahedral meshing and static analysis type is chosen for simulation. The dimensions and material properties are listed in table 1 [1]. To verify the accuracy and validity of simulation model, a FEA model for the multi layer piezoelectric actuator is built up and compared with the results in the literature (Jianke Kang and Gregory W. Auner, 2011). The driving voltage for simulation is 240 V(zero to peak). The first simulation is perform by imposing 240 V DC voltage on piezoelectric layer and pressure of the passive silicon plate is kept zero. The result of simulation shows the average diaphram displacement along the diagonal distance of the plate. The maximum diaphragm displacement is 9.79 µm corresponding to 4.27 mm daigonal distance of plate as shown is fig 3B and fig 3A shows the contour view presenting diaphragm deformation of the layer. As outlet valve of micro pump get close, it exert a back pressure on the diaphragm.

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Table 1- Material properties and dimensions of three layers

Layer Dimension	Material properties	Value of material properties
Silicon 5 mm × 5 mm × 40 µm	Young's modulus Poisson ratio	170 GPa 0.3
Epoxy H31 4 mm × 4 mm × 20 µm	Young's modulus Poisson's ratio	5 GPa 0.3
PZT-5A 4 mm × 4 mm × 127 µm	Compliance	$\begin{bmatrix} 19.2 & -5.74 & -7.22 & 0 & 0 & 0 \\ -5.74 & 19.2 & -7.22 & 0 & 0 & 0 \\ -7.22 & -7.22 & 15.1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 47.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 47.5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 44.3 \end{bmatrix} \times 10^{-12}\ m^2/N$
	Piezoelectric coupling	$\begin{bmatrix} 0 & 0 & -190 \\ 0 & 0 & -190 \\ 0 & 0 & 390 \\ 0 & 584 & 0 \\ 584 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \times 10^{-12}\ C/N$
	Relative permittivity	$\begin{bmatrix} 1800 & 0 & 0 \\ 0 & 1800 & 0 \\ 0 & 0 & 1800 \end{bmatrix}$

As the value of back pressure increases, the average diaphragm displacement is dicreases and for particular value of back pressure, the average diaphragm displacement became almost zero.So several simulation are perform by increasing the value of back pressure for same voltage. Fig 3D shows that the value of average diaphram displacement remains 2.24 µm as value back pressure increases upto 11.93×10^5 N/m². Fig 3C shows the contour view presenting diaphragm deformation of the layer for 11.93×10^5 N/m² back pressure and 240 DC voltage. The experimental data indicates that when the backpressure is increased by 6.89×10^3 N/m², the stroke volume is reduced roughly by 3.75 nl. After the simulation, it is found that the maximum deflection of the piezoelectric diaphragm is 9.79 µm and the deviation of simulation result from the

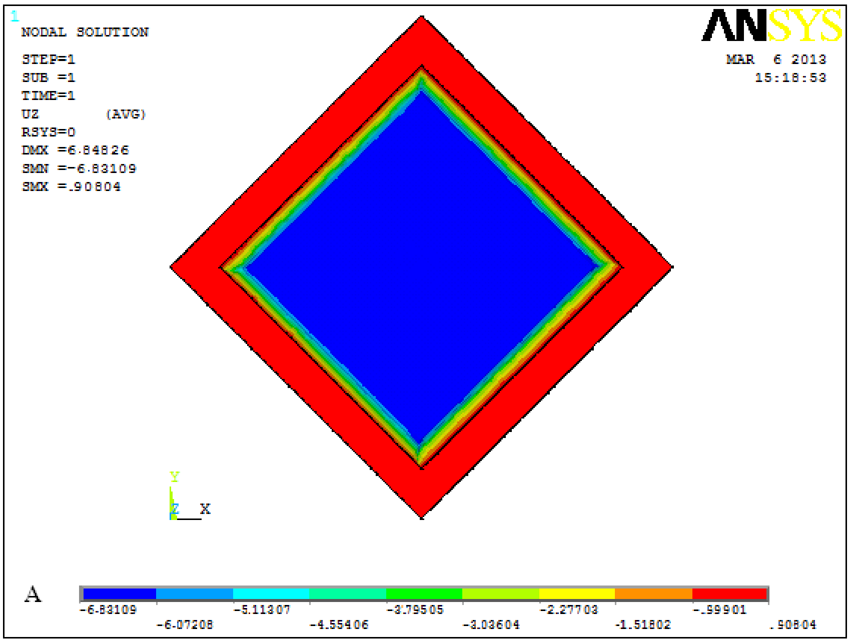

Fig. 3 (A) Contour view of the diaphragm at 240 V

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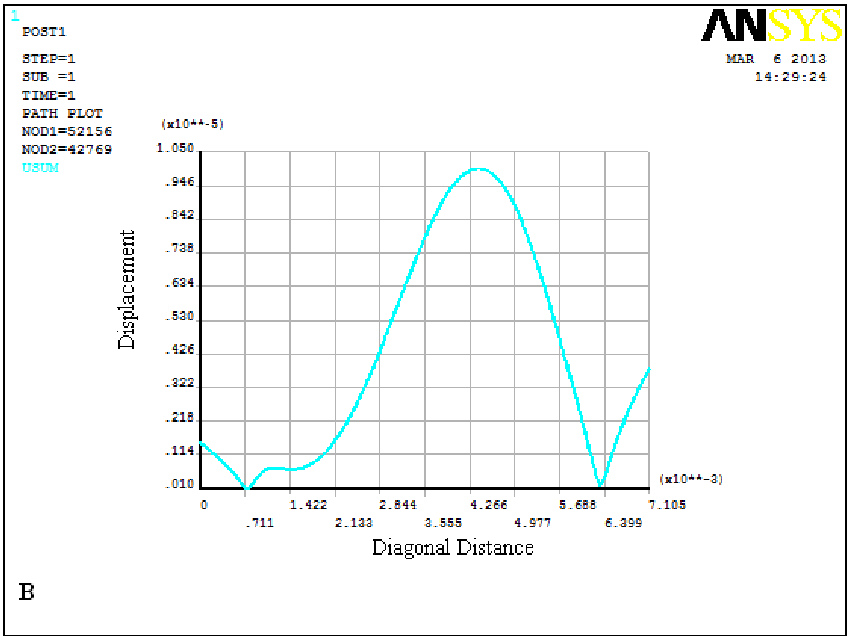

Fig. 3 (B) Shows the deflection of diagonal distance at 240 V.

experimental result is less than 10% which shows that the simulation model in the present work is valid. The defferances between the simulation and experimental results are mainly because of :

(1) In experiment, due to practical limitation in opening and closing of check valve a small backflow of fluid is take place which reduce the deflection of diaphragm.

(2) The glueing of piezoelectric layer is a difecult process because coating of epoxy layer is not uniform.

(3) Electrode connection may reduce the effectiveness of the diaphragm.

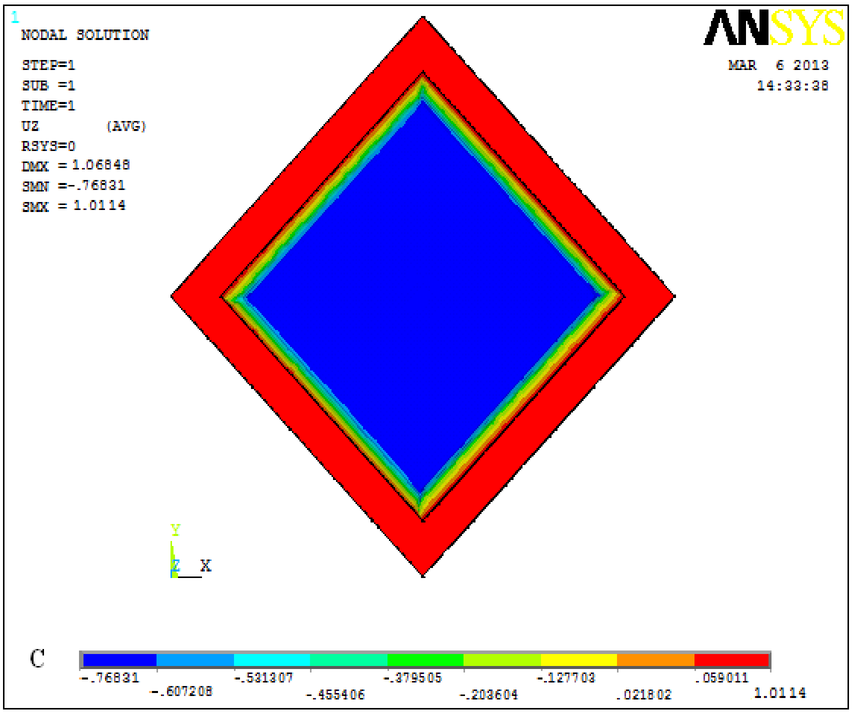

Fig. 3 (C) Contour view of the diaphragm at 240 V and 11.93×10^{5} N/m². Backpressure

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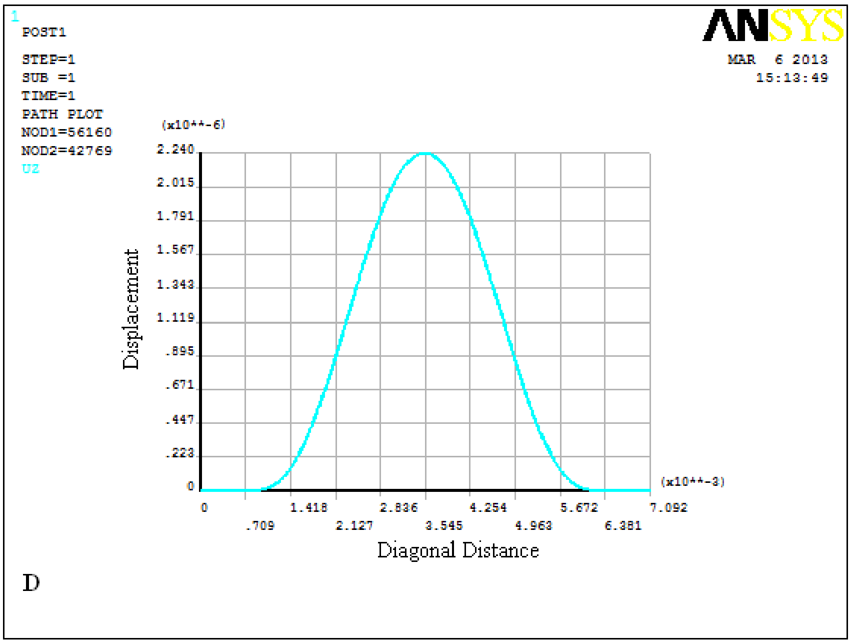

Fig. 3 (D) Shows the deflection of diagonal distance at 240 V and 11.93×10^5 N/m².backpressure.

VI. CONCLUSION

The Finite Element Model for the ractangular piezoelectric actuator of the check valve micropump is simulated using Finite Element Analysis ANSYS software. In this analysis, the average diaphragm displacement concept is used to establish the relationship between diaphragm displacement and backpressure of a check valve micropump. The average diaphragm displacement is taken along the diagonal distance of the diaphragm plate.The deflection of the diaphragm at 240 V (fig. 3b) shows that the maximum deflection is not lie at the centre in case of ractangular diaphragm. So, Average diaphragm displacement concept is more suited to evaluvate the performance of the micropump instead of centre displacement method because it gives the displacement at every point of diaphragm. As the backpressure on diaphragm increases, the deflection of diaphragm gradualy decreases and at 11.93×10^5 N/m² its value is decreases upto 2.24 µm. This deflection is not sufficient to deliver the fluid. So delivery of fluid is limitedted at 11.93×10^5 N/m² because deflection of diaphragm became almost zero. The result of simulation at higher voltage shows that the maximum diaphragm displacement is away from the centre of the diaphragm and as the backpressure on the diaphragm plate is gradualy increases, the maximum deflection is shifted toward the centre of the diaphragm. The deviation of maximum defletion from the centre implies that instead of centre displacement, average displacement is more suited for the analysis of piezoelectric diaphragm. The study will help in analysing micropump parameter for different application in the area of biomedical instrumentation and other fluidic control activity in manufacturing.

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