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TECHNICAL PAPER

Modeling of single and multilayer polyvinylidene fluoride film for micro pump actuation

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Abstract Micro pumps are essential components of micro devices such as drug delivery systems. Large numbers of pumps have been proposed based on different actuating principles. Piezoelectric actuation offers advantages such as reliability and energy efficiency. Lead zirconate titanate (PZT) based piezoelectric actuation for micro pumps is predominantly explored despite its disadvantages such as brittle nature, low straining and difficulties in processing. Polymer piezoelectric materials like polyvinylidene fluoride (PVDF) could be promising replacements for PZT owing to their availability in form of films and good strain coefficients. Very limited literature on micro pump with PVDF as an actuator is available. In this paper, finite element analysis (FEA) model of a micro pump actuator using single and multilayer PVDF for actuation is developed in ANSYS®. The model takes into account the influence of driving voltage and actuator geometry. The central deflection of the pump diaphragm which is instrumental in defining the pump performance is studied for driving voltages of 100–200 V. The deflection of the pump diaphragm for single layer and multilayer actuation are determined from the model. It could be inferred from the initial part of the study that pump performance depends on driving voltage and actuator film thickness. In order to reduce driving voltage requirement multilayer stacked actuator is tried with four different configurations of the layers. It is concluded that stacking configuration of parallel energized straight polarity PVDF layers yielded best central deflection. An attempt is made to compare the performance of multilayer actuator with an equivalent single thick layer actuator. It is noticed that the multilayer actuator performance was better by about 101% when number of layers is doubled.

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1 Introduction

Micro-devices are used for precise delivery of drugs either in an implanted or transdermal form. These devices dispense minute quantities of drugs as opposed to diffusion based conventional system of drug delivery. Micro devices are simple drug reservoirs that dispense drug in response to external commands. Recent smart systems among these offer closed-loop sensing and assaying with onboard interpretation of results and automatic titration of drugs (or hormones). For example, in asthma treatment an implanted airway sensor or acoustic device determines the presence of bronchospasm and the drug delivery system (DDS) releases certain amount of bronchodilator. The convenience, better response time, and precise regulation of medical condition are the driving forces for the development of these systems (Saliterman 2006).

Micro pumps are indispensable components of a DDS mentioned above. These micro pumps work on different actuating principles such as thermopneumatic, electrostatic, shape memory alloy, electromagnetic as well as piezoelectric. Among the different actuating principles, piezoelectric actuation offers advantages such as low flow rates, moderate pressures at low power, good reliability and energy efficiency, which are preferred for DDS. As micro

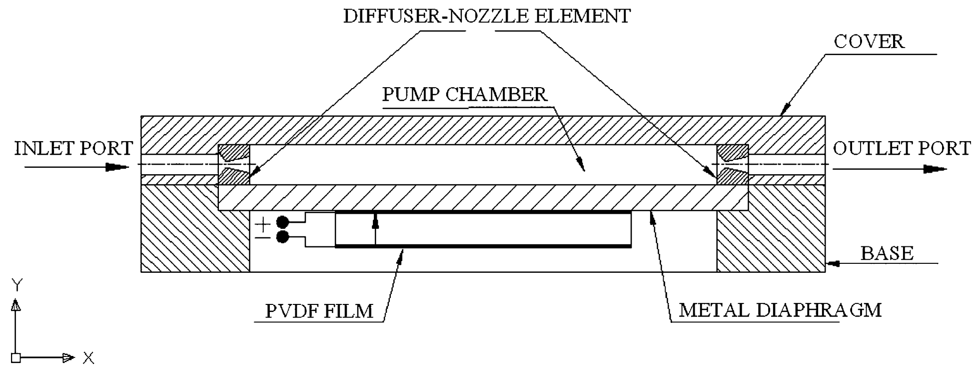

Fig. 1 Configuration of the micro pump

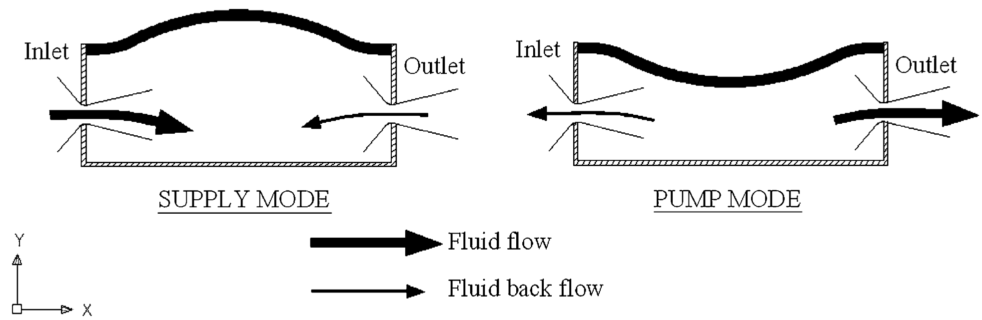

Fig. 2 Operation of the micro pump

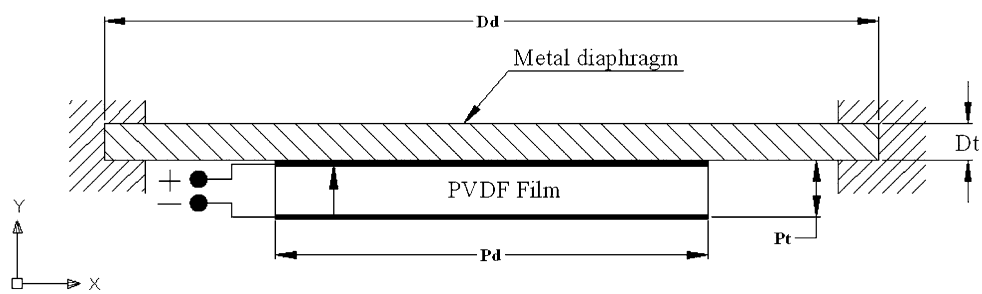

Fig. 3 Actuator for the micro pump

Table 1 Actuator parameters (Ullmann et al. 2001)

Metal diaphragm diameter D_d (mm)	10
Metal diaphragm thickness D_t (mm)	0.15
PVDF film diameter P_d (mm)	8
PVDF film thickness P_t (mm)	0.028, 0.052, 0.110

pumps used in DDS need reliability and service life, designs with no moveable valves and parts are preferred (Mu et al. 1999). Amongst different attempts to design micro pumps with non moving valves, diffuser nozzle geometry for inlet and outlet suggested by Stemme and Stemme (1993) is most widely used. Few earlier studies on the performance of micro pump with piezoelectric actuation and valve-less geometry are available in the literature (Ullmann 1998; Ullmann et al. 2001; Ullmann and Fono 2002).

The piezoelectric valve-less pump consists of a diaphragm activated by a piezoelectric disk. Piezoelectric materials such as lead zirconate titanate (PZT) or zinc oxide are well explored because of their relatively large piezoelectric coefficient. At the same time, difficulties in deposition of these films, large Young's modulus resulting in smaller strain, and their brittle nature pose few problems and challenges for the designer and manufacturer. Piezoelectric polymer film of polyvinylidene fluoride (PVDF) could be used in their place. The lower Young's modulus of these films facilitating large strains and hence large displacements/deflections are achieved. Reliability and service life with such PVDF film actuation are also expected to be more on account of above properties. Literature on the performance of such micro pumps is scarcely available, hence in this paper, a study of PVDF actuation in valve-less micro pump is envisaged.

Behavior of PVDF as an actuator for micro pumps is studied based on the pump design suggested in the earlier literature (Ullmann 1998; Ullmann et al. 2001; Ullmann and Fono 2002). The proposed actuator consists of an Aluminium circular diaphragm with PVDF film glued to it. As the pump performance greatly depends on the deflection

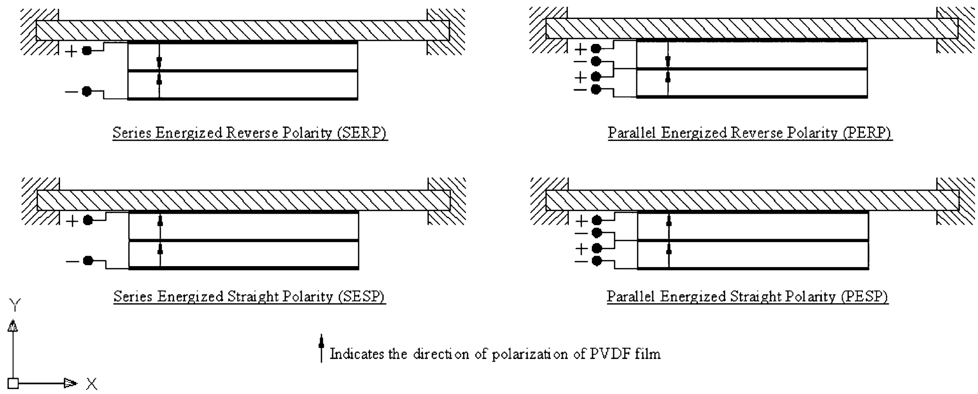

Fig. 4 Configurations of PVDF layers for multilayer actuation

Table 2 Elements used in modeling actuator

Part	Material	Element type	Young's Modulus E GPa	Poisson's Ratio
Metal diaphragm	Aluminium	Solid 95	73	0.33
Actuator	PVDF	Solid 226	8.3[a]	0.18[a]

[a] As per the specification of the supplier

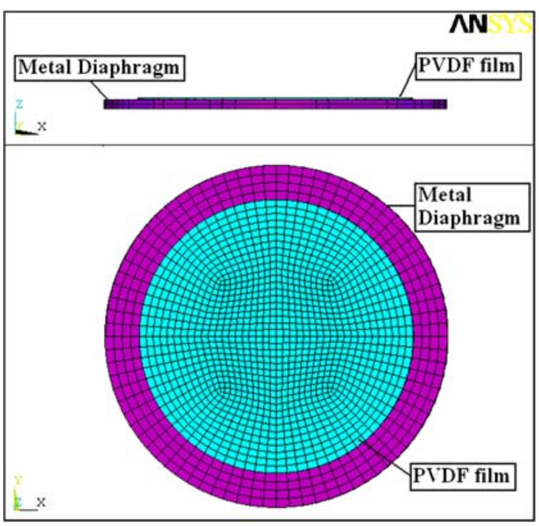

Fig. 5 Generated mesh of the diaphragm and the PVDF

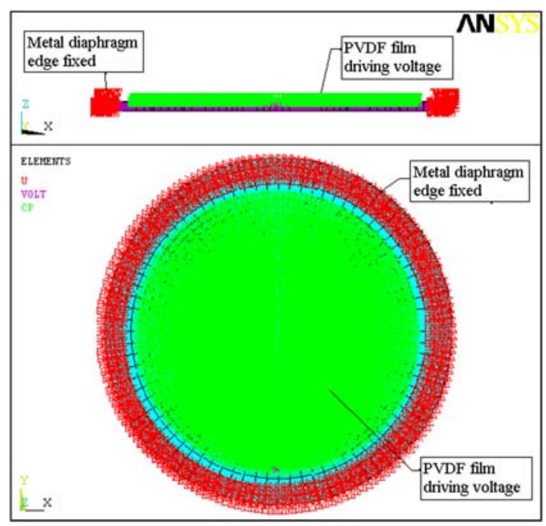

Fig. 6 Loading and boundary conditions

of the diaphragm, the central deflection of the diaphragm is evaluated for different configurations of actuator such as single layer/multilayer stacked form. The pump diaphragm deflection for different actuator configurations is modeled using a commercial finite element based modeler ANSYS®.

2 Principle of actuation in micropump

The pump configuration considered for modeling of actuator is shown in the Fig. 1. In the pump configuration considered, valves are replaced by diffuser-nozzle elements at the inlet and outlet ports of the pumping chamber. The pump operates in two modes, the supply mode and the pump mode. The pump operation is shown schematically in Fig. 2. The volume of fluid flowing in the diffuser direction is higher than the volume of fluid flowing in the nozzle direction as depicted in the Fig. 2. During the supply mode, the cavity volume of the pumping chamber increases, a large quantity of fluid enters the chamber through the inlet port acting as a diffuser element, than the outlet port acting as a nozzle element. During the pump mode the cavity volume of the pumping chamber decreases, a large amount of fluid flow out of the chamber through the outlet port, which acts as a diffuser than through the inlet port, which

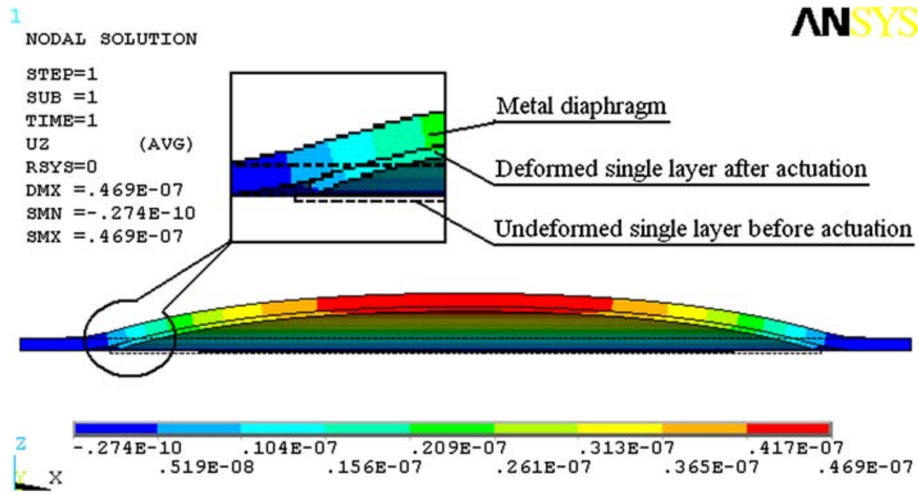

Fig. 7 Displacement plot for single layer 28 μm thick PVDF film actuation at 100 V

acts as a nozzle. The combined two modes result in one complete pump cycle, where a net volume of fluid is transported from inlet to outlet port of the pump (Olsson et al. 1995).

The actuation of the diaphragm is responsible for pumping action and is achieved by attaching a piezo actuator to the diaphragm. To assess the use of PVDF as a piezo actuator, the diaphragm and the piezo film attached to it are considered for analysis. The configuration is shown in Fig. 3. For a particular geometry, pump performance is determined by the disk displacement brought out by the actuator. Initially the disk deflection for a single layer PVDF actuation is studied by modeling it in ANSYS®. The parameters considered for modeling of the piezo actuator and diaphragm are tabulated in Table 1.

The effect of increasing the film thickness and driving voltage on deflection of actuator is studied for three film thickness values (0.028, 0.052, 0.110 mm) and six different driving voltages (100–200 in steps of 20). On account of low piezoelectric coefficient and low dielectric constant, the electrical impedance of PVDF is expected to be high. Thus, for large central deflection, higher driving voltage is required or higher thickness PVDF film is required. Both of these result in structural problems. Hence one of the means for achieving maximum central deflection is the use of multiple layers of PVDF film. To maximize the disk displacement and hence the pumping action at low actuation voltage, multilayer stacking of PVDF film is considered. The stacking can be done in different configurations. The layers can be energized electrically in parallel or in series and the stacking of the film can be done with all layers having straight polarity or alternating layers having reverse polarity. Four sets of configurations are possible and they are: Series energized films having straight polarity stacking (SESP); Series energized films having alternative reverse polarity stacking (SERP); Parallel energized films having straight polarity stacking (PESP); Parallel energized films having alternative reverse polarity stacking (PERP). Different configurations used for multilayer actuation of the micro pump considered in the analysis are shown in the Fig. 4.

3 Modeling of PVDF actuator

The PVDF film actuator and the metal diaphragm shown in Fig. 3 are modeled using a commercial finite element model (FEM) software package ANSYS® version 10.0. Details of elements and materials used for modeling the actuator for the micro pump are given in Table 2. The generated mesh of the metal diaphragm and the single layer PVDF film actuator is shown in Fig. 5. The loading and boundary conditions on the FEA model for same are shown in Fig. 6.

The central deflection response for four configurations of multilayer actuator mentioned earlier are modeled on similar lines as single layer PVDF film actuator and the results are presented in the next section.

4 Results and discussion

4.1 Single layer actuation

Deflection of the diaphragm is modeled as detailed in the previous section. Figure 7 shows the deformed shape of the diaphragm for 100 V driving voltage and PVDF film thickness of 28 microns. The central deflection response of disk for 28, 52 and 110 microns thickness and six driving voltages 100–200 V in steps of 20 V are studied and the results are presented in Table 3. It can be observed from the data in Table 3 that the central deflection is proportional to

Table 3 Central deflection of metal diaphragm with single layer actuation

Actuation Voltage (V)	Central deflection of metal diaphragm in microns		
	Film thickness 28 μm	Film thickness 52 μm	Film thickness 110 μm
100	0.0469	0.0543	0.0688
120	0.0563	0.0651	0.0825
140	0.0657	0.0760	0.0963
160	0.0751	0.0868	0.1100
180	0.0845	0.0977	0.1238
200	0.0939	0.1085	0.1376

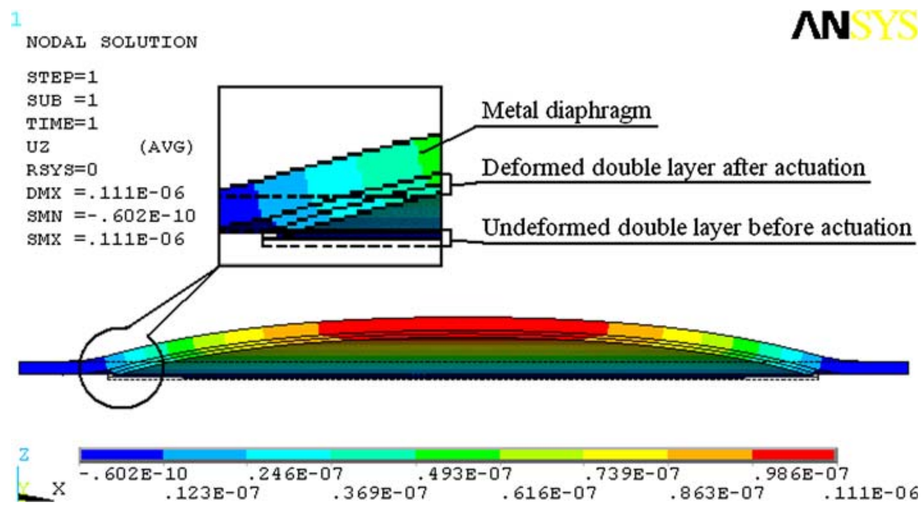

Fig. 8 Displacement plot for double layer of 28 μm thick PVDF film actuation at 100 V

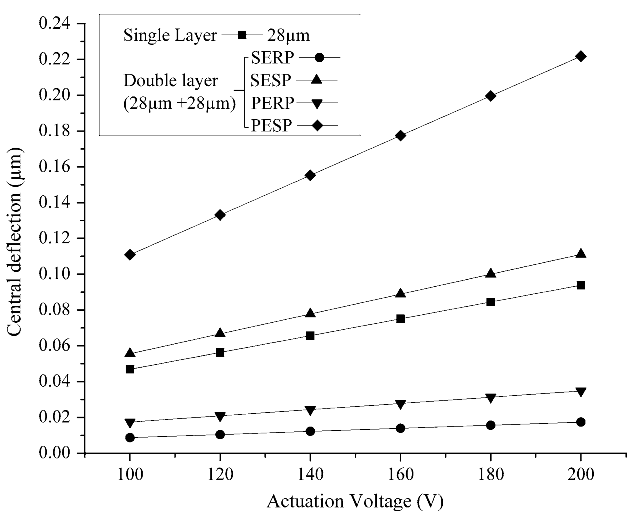

Fig. 9 Central deflection for various stacking configuration

the input voltage and thickness of the PVDF film. A high input voltage and a thicker PVDF film can produce a large central deflection and can give a better flow. High voltage poses some disadvantages in practice, as it affects the structure as well as the control system. In order to reduce the driving voltage requirements, multilayer actuator is considered. The results of multilayer actuation analyses are presented in the next section.

4.2 Multilayer actuation

Figure 8 shows the diaphragm deflection for a double layer actuator with PVDF film thickness of 28 microns and layers set in different configurations as shown in Fig. 4. The central deflection for various stacking configurations is displayed in Fig. 9. From the figure it can be inferred that stacking configuration also influences the central deflection of the diaphragm apart form the driving voltage. The response is significantly better for the PESP. This could be due to strains of individual layers augmenting each other in this configuration.

Pump performance in terms of the central deflection of the diaphragm can be enhanced in two ways; by resorting to thicker actuator as shown in Table 3 or stacking of actuator layers with reference to Fig. 9. Figure 10 represents comparison of the response of a double layer stack (28+28) microns with a single layer actuator of 52 micron thick. From this plot, it can be noticed that double layer PESP configuration has much better central deflection of the diaphragm as compared to single layer actuator having

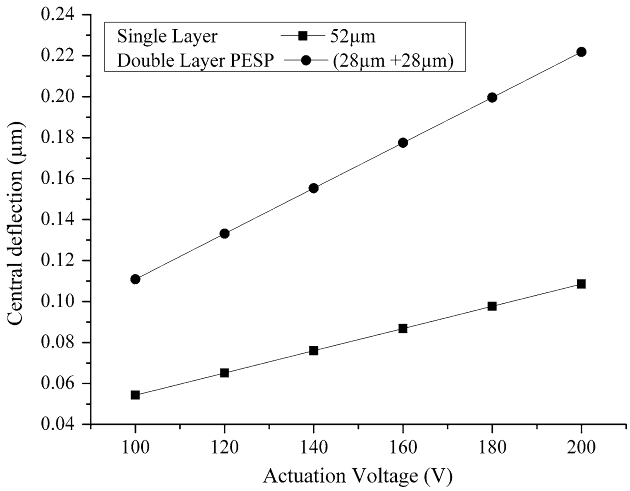

Fig. 10 Comparison of central deflection for single layer and double layer actuation

Table 4 Central deflection for constant stack thickness and increase in no of layers

Stack thickness (µm)	Thickness of each layer (µm)	Number of layers	Central deflection (µm)
110	110	1	0.0688
110	55	2	0.1379
111	37	3	0.2078
112	28	4	0.2776

nearly the same thickness as of stack. Results of another attempt to ensure the effect of layer thickness in a multi-layer actuator stack are presented in Table 4. It can be observed from the table that for a constant stack thickness of 110 microns, stack having more number of layers with smaller layer thickness yields better central deflection of the diaphragm. This inference is in line with that of earlier research work where acoustic power outputs with multiple-layer stack are studied (Swartz and Plummer 1980).

5 Conclusions

In this paper, investigations on various aspects of using PVDF as an actuator in a micro pump are explored. ANSYS® modeling of pump diaphragm deflection for single layer and multilayer actuation of PVDF film is studied. In the case of single layer actuation, it could be inferred that increase in driving voltage and layer thickness will appreciably improve central deflection of the diaphragm. Single layer PVDF requires high magnitude of driving voltage to achieve appreciable central deflection of the diaphragm. Larger central deflection could be achieved by multilayer stacking minimizing voltage requirement. The various configurations of stacking PVDF are modeled and among them the PESP scheme is found to be yielding maximum central deflection of the pump diaphragm. It is also attempted to study the effect of increasing number of layers in the multilayer stacking. The central deflection of the diaphragm was enhanced by increasing the number of layers. The central deflection increased by 104% for double layer actuator in comparison to single layer. When number of layers was doubled, say from 2 to 4, the central deflection increased by about 101%. It could also be inferred that the response could be improved by going for larger number of thinner layers than a single thick layer.

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