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A modeling and vibration analysis of a piezoelectric micro-pump diaphragm

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ABSTRACT

The vibration analysis of a micro-pump diaphragm is presented. A piezoelectric micro-pump is studied. For this purpose, a dynamic model of the micro-pump is derived. The micro-pump diaphragm is modeled as circular double membranes, a piezoelectric one as actuator and a silicon one for representing the membrane for pumping action. The damping effect of the fluid is introduced into the equations. Vibration analysis is established by explicitly solving the dynamic model. The natural frequencies and mode shapes are calculated. The orthogonality conditions of the system are discussed. To verify the results, the finite-element micro-pump model is developed in ANSYS software package. The results show that the two methods are well comparable.

1. Introduction

The emergence of micro-fabrication in the last decade has introduced new ways to miniaturize many devices. One of the important uses of this technology is in drug-delivery systems. Some diseases respond differently according to the drug dose that is introduced into the human body. Therefore, the needs for analysing and controlling these systems are inevitable. Micro-pumps are an essential part in drug delivery systems for this purpose. Designing a micro-pump is a challenging task due to its important role. Nan-Chyuan Tsai [1] offers a fine review of different types of micro-pumps and of their mechanisms.

Typically, a piezoelectric micro-pump consists of a silicon membrane (S-membrane) which is actuated with a piezoelectric membrane (P-membrane) connected to it. By actuating the piezoelectric membrane in the resonant frequency, the highest efficiency can be achieved. Fig. 1 shows the schematic for a piezoelectric micro-pump.

Researchers have paid more attention to piezoelectric micro-pumps among all other types due to their controllability and reliability. Bart [2] worked on electrohydrodynamic (EHD) micro-pumps. This type of pumping uses the interaction of electric field and charges in the fluid to create the force for moving the fluid. Smits [3] modeled a piezoelectric micro-pump that was working peristaltically and had three valves. A fixed-valve micro-pump was designed and fabricated by Forster et al. [4]. Gerlach [5] designed and implemented a dynamic micro-pump with nozzle and diffuser as the inlet and outlet of the pump. He studied the dynamics of a fluid in the pump, and a static model for the membrane was derived. Olsson [6] fabricated a valveless micro-pump with double chamber. Das et al. [7] designed a control mechanism for controlling the flow of the micro-pump by modulating the electrostatic force. Johari [8] has designed a valveless piezoelectric micro-pump. However,

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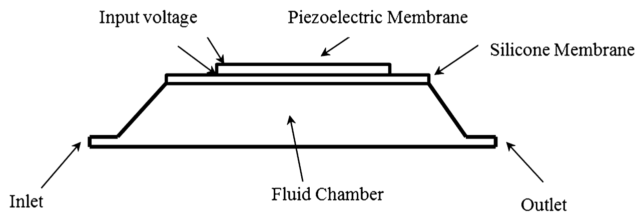

Fig. 1. Schematic view of a piezoelectric micro-pump [16].

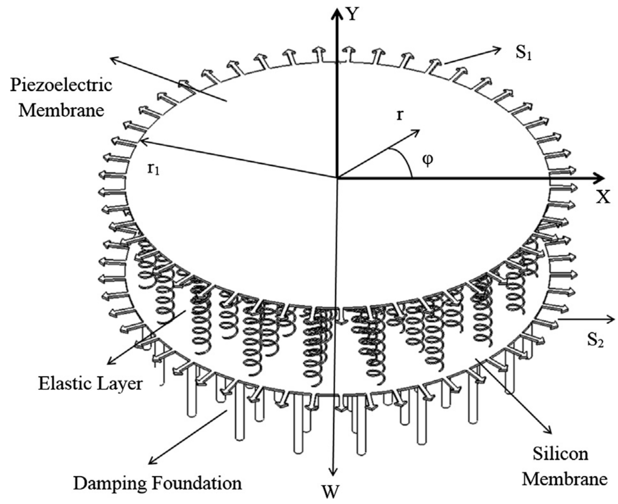

Fig. 2. Schematic view of the membrane in micro-pump.

the operation of this micro-pump has not yet been investigated theoretically in full detail. A software simulation with no theory has been reported in [9]. In lieu of all the works done on micro-pumps, it still remains to see the comprehensive model of the micro-pump for detailed analysis design purposes.

Ayela [10] modeled two membranes with a surrounding fluid. However, the two membranes were assumed as one with averaged mass. Energy methods and assumed mode shape were used to solve the problem. Cho et al. [11] modeled a two-layer membrane, one with piezoelectric material. Coupling has also been investigated, while a lumped parameter model is used to find the effect of the electromechanical coupling coefficient. Yih [12] used the pressure change in the micro-pump to derive the equations. Pan [13] modeled a micro-pump as only one membrane and added the effect of the piezoelectric membrane by importing an excitation force into the equation, and using thin plate theory to solve the problem. Oniszczuk [14] solved the problem of free and forced vibrations of a rectangular compound membrane. Noga [15] found the solution for the free transverse of a circular compound membrane. In both articles, the damping effect had been neglected.

Here, the piezoelectric micro-pump has been modeled as a two-membrane one, the membranes being elastically connected to each other. The damping effect of the fluid is added to the formulation as a viscose effect, related to the velocity of the membrane. An analytical solution has been attained for this model. Natural frequencies and mode shapes were calculated. Then orthogonality conditions have been discussed.

2. Dynamic model of the system

Fig. 2 shows the schematics of a circular double-membrane system. The membranes are assumed to be homogenous and are connected through a linear, massless elastic layer. The fluid has been assumed as a damping foundation beneath the silicon layer (not shown in this figure).

In this figure, r_1 is the radius of the membranes; S_1 and S_2 are the uniform constant tensions per unit length applied on the first and the second membrane, respectively, and w is the transverse of the membranes.

The system of equations for the system shown in Fig. 2 can be written as follows:

$$\begin{cases} m_1\ddot{w}_1 - S_1\Delta w_1 + k(w_1 - w_2) = f_1 \\ m_2\ddot{w}_2 - S_2\Delta w_2 + k(w_2 - w_1) + c\dot{w}_2 = f_2 \end{cases} \tag{1}$$

where w is a function of r, φ and t in polar coordinates. k is the stiffness coefficient of the elastic layer (elastic foundation of Winkler type between P- and S-membranes), and c is the damping coefficient of the fluid surrounding the second (silicon) membrane.