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A LOW COST PIEZOELECTRIC VALVE-LESS DIAPHRAGM PUMP

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Abstract. *Flow pumps act as important devices in areas as Bioengineering, Medicine, Pharmacy, among other areas of Engineering. Principles for pumping fluids based on piezoelectric actuators have been studied in the Department of Mechatronic and Mechanical Engineering of University of São Paulo, that allow the construction of small flow pumps, in other words, pumps for displacement of small fluid volumes with low power consumption. The present work studies valve-less piezoelectric diaphragm pumps for flow generation. The piezoelectric diaphragm flow pump uses a piezoelectric ceramic as actuator to move a membrane (diaphragm) up and down as a piston. Consequently, there is a sequence of increase and decrease in the chamber volume that will force the fluid in and out of the pump. The direction of the flow is guaranteed by nozzle/diffuser elements that privilege the flow in just one pumping direction. The main objective of this work is the study of a methodology to develop a low cost valve-less piezoelectric diaphragm flow pump. A complete cycle of pump development is conducted in this work, consisting in designing, manufacturing, and experimental characterization steps. In the design step, sensitivity studies are performed using computational simulations through the Finite Element Method (FEM) to analyze effects of geometric and assembly parameter variation in the pump behavior. Moreover, the CFD simulations are performed to study the fluid flow inside the pump, as well as the performance of the designed nozzle/diffuser elements. The prototype manufacturing is guided by computational simulations. Low cost machining and electro-erosion are used as manufacturing processes. Pressure and flow characterization experimental tests are conducted and comparisons among numerical and experimental results are made to validate the computational results, improving the accuracy of the implemented models.*

Keywords*: piezoelectric actuator, flow pump, CFD, FEM, microfluidics*

1. INTRODUCTION

Recently, piezoelectric ceramics have been investigated as an interesting alternative in the construction of precision flow pumps, that is, small size devices for pumping small fluid volumes (Laser and Santiago, 2004). These devices have lower noise generation, fewer numbers of moving parts, and provide low power consumption and, thus, it can be applied as an essential component of several pumping systems. The Bioengineering is an area that has been demonstrated great interest for this type of equipment. In this area it can be used for continuous injection of insulin in diabetic patients during the day (Teymoori and Abbaspour-Sani, 2005), removing outbreaks and deficits of this substance, and for pumping of biological fluids (Andrade et al., 1996), for instance. Other possible application is in chemical reagents dosage in portable equipments utilized for clinical analyses (Tsai and Sue, 2007).

New principles of pumping fluids have been extensively proposed for piezoelectric flow pumps. One of them has been developed by research group of the Department of Mechatronic and Mechanical Engineering of University of São Paulo, which pump configuration is based on placing an oscillating bimorph piezoelectric actuator in a fluid channel to generate flow (Lima et al., 2009). The proposed principle of pumping mimics a phenomenon of the swimming fish (Sfakiotakis et al., 1999). Other principle is found in the ultrasonic pump (Bar-Cohen and Chang, 2001) which uses stators piezoelectrically actuated to generate a propagating wave that moves the fluid. The movement obtained in this flow pump is similar to the peristaltic movement, which is observed in the human esophagus.

Another area that has interest in piezoelectric flow pump is the cooling systems for electronic equipments (Singhal et al., 2004), such as high performance computers and notebooks. However, for this application a pump system must provides a lot of pressure due to high load loss located in heat exchangers. Then, it is possible to reach larger pressures when the diaphragm pump is used. The first piezoelectric diaphragm pump was presented by Van Lintel et al. (1988), which uses diaphragm passive valves. It consists of an extern flexible ring and of a rigid central ring. The active pressure in this kind of pump bends the extern flexible ring and, then, it seals the internal ring.

Various passive valves design based on flaps or other moving structures have been proposed for diaphragm pumps, such as the ones in which a piezoelectric actuator known as “stack” type is connected to the diaphragm (Esashi et al., 1989), and another that uses sphere valves to rectify the flow (Carrozza et al., 1995). A type of diaphragm valve very explored in the literature is the one known as “cantilever” (Zengerle et al., 1995). This passive valve has a clamped beam structure that bends when active pressure acts, allowing the flow. In all of these kinds of diaphragm pump, cited before, the direction of the flow is guaranteed by passive valves that allow unidirectional flow. However, flow pumps with movable parts can have problems such as elevated pressure drop and fatigue. Besides, the resonance frequency of the passive valves must be near to the resonance frequency of the actuator. It is necessary to obtain movement synchronizations between the expansion and contraction of the diaphragm and the opening and closure of the valves, otherwise flow pump will have cavitations. Moreover, it is difficult to construct it by using conventional manufacturing processes, which turns flow pump cost very high.

Thus, this work aims to develop a low cost piezoelectric diaphragm pump based on the referred “no-moving-parts” valves, or, simply, “valve-less” pump configuration (Stemme and Stemme, 1993). Figure 1 illustrates this kind of diaphragm flow pump.

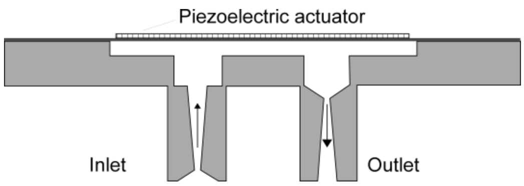

Figure 1. A valve-less flow pump scheme

The main characteristic of a valve-less flow pump is the channel geometry of nozzle-diffuser elements of fluid inlet and outlet of pump chamber, where the pressure drop in the direction of the diffuser is less than the pressure drop in the direction of the nozzle, considering the same flow velocity for both directions. During the suction phase, when the pump chamber volume increases, the inlet channel provides low restriction to fluid entrance in the cavity, that is, it acts as a diffuser. Whereas, outlet channel drives high restriction for fluid exiting the cavity, then, it acts as a nozzle. During the discharge phase, when cavity volume decreases, a large quantity of fluid leaves the camera through the outlet channel, which in this situation acts as diffuser, whereas the inlet channel acts as nozzle, expelling a small quantity of fluid. The result of a complete pumping cycle is the transport of fluid from the flow pump inlet to the outlet, in spite of the nozzle-diffuser system allowing fluid flow in two directions.

The development of the piezoelectric valve-less diaphragm pump proposed in this work is presented in next sections. Section 2 describes the fundamental theory. Section 3 shows analysis of proposed flow pump using computational simulations. Section 4 describes the experimental characterization and results achieved using a manufactured prototype. Finally, in Section 5 some discussion of the obtained results and conclusion is provided.

2. FUNDAMENTAL THEORY

The diaphragm shown in Fig.2 is applied to flow pump analyzed in this work. This piezoelectric diaphragm is formed by three layers: the ceramic piezoelectric disk, the glue layer, and the passive membrane. When an electric field is applied to the piezoelectric disk terminals, the membrane bends toward its perpendicular direction surface. As the contour of membrane is clamped (see Fig. 2b), it presents a concave or convex deformation which yields the pumping effect that generates fluid flow through the diaphragm pump. In this case, the piezoelectric ceramic has a piston-like behavior, because when the diaphragm moves, reducing the pump chamber volume, the fluid is expelled from flow pump. Otherwise, when the diaphragm movement increases the pump chamber volume the fluid entries to the chamber.

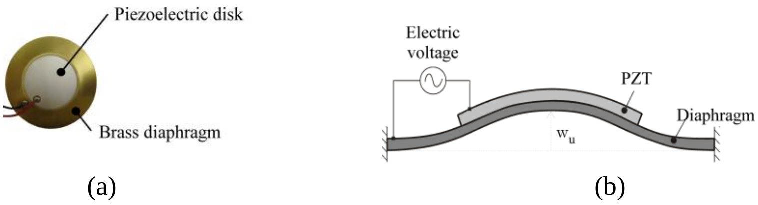

Figure 2. (a) Piezoelectric disk and metal membrane; (b) lateral view scheme of the piezoelectric diaphragm

The piezoelectric ceramic is capable of converting electric energy into mechanical energy and vice-versa. The flow pump diaphragm used in this work is an electromechanical device with high bending degree. The actuator (piezoelectric disk of Fig. 2) is constructed by using a piezoelectric ceramic layer (PZT) bonded to a metallic plate (cupper or brass) through a conductive epoxy sticker (glue layer). When an electric voltage is applied to the piezoelectric ceramic, the metallic plate is deformed proportionally to the applied voltage. This piezoelectric actuator can generate displacements

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less than 1 mm. The piezoelectric actuator is excited by harmonic or squared waves with frequencies around 100 Hz and applied voltage around 60~120 V, depending on the dimensions and on the geometry of the actuator.

3. COMPUTATIONAL SIMULATION

3.1. Modelling procedure

It is possible to calculate analytically flow rate generated in a diaphragm pump through the difference between the expansion and contraction chamber volumes (Stemme and Larsson, 1973), however an analytical formulation more detailed for the flow pump behavior could be very complex. Thus, in this work the diaphragm flow pump is analyzed numerically through computational simulations using the finite element method.

The ANSYS finite element software is used for the diaphragm piezoelectric pump computational simulations, since its finite elements library (Ansys, 2007) covers a wide range of physical phenomena as required in this work. Computational simulations are carried out in four steps, as depicted in Fig. 3. First, a computational model of the piezoelectric actuator surrounded by air is created. From harmonic analysis, simulations in this step must provide resonance frequencies and vibration modes close to real piezoelectric actuator. Second, from harmonic analysis in water medium, a sensitivity analysis is carried to study how construction parameters and assembly affect diaphragm flow pump performance. Third, another sensitivity analysis is done around valves geometrical parameters. From fluid flow analysis, using amplitude and frequency data obtained in first step, this sensitivity analysis aims to found optimum nozzle/diffuser geometries for maximizing flow rate and pressure output. Finally, using the results obtained in the previous steps, a complete modeling of the diaphragm flow pump is carried out. The modeling applied to this step is more detailed than the one used in the previous steps. Using all compiled results obtained in sensitivity analyses, the piezoelectric diaphragm pump fluid medium is modeled (fluid flow analysis), using moving boundary conditions to simulate the pumping system.

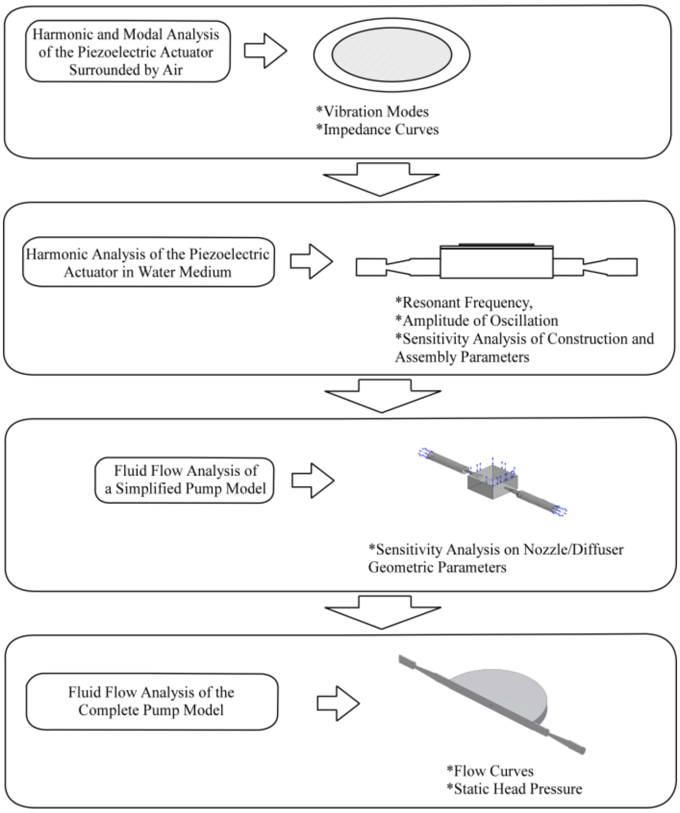

Figure 3. Computational simulation steps

To simulate the piezoelectric actuator in air (harmonic analysis) the SOLID98 element is used, which is capable of simulating both structural and piezoelectric effects. The pump chamber medium is modeled by using the FLUID30 element, which has displacement and pressure degrees of freedom and it allows modeling fluid-structure interaction. It is observed that the simulation using FLUID30 element aims at studying the piezoelectric actuator behavior inside water medium (acoustic analysis). For fluid flow simulation, the FLUID142 element is used. This element has velocity components, pressure, and temperature degrees of freedom and is capable of simulating laminar or turbulent flows in permanent or transient state (Ansys, 2007).

3.2. Simulation results

The adopted dimensions of the piezoelectric actuator model can be seen in Fig. 4. The employed materials in this model are brass (metallic plate) and PZT-5A (piezoelectric disk).

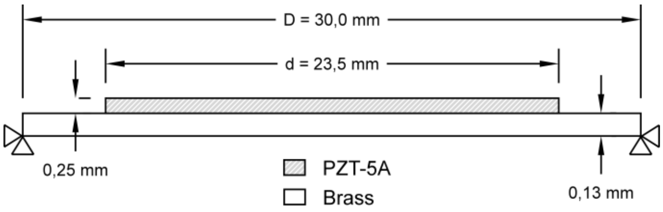

Figure 4. Piezoelectric actuator model

The FE mesh considered in the simulation of the piezoelectric actuator in air has 31,390 elements. The boundary conditions for this model are: clamped piezoelectric actuator contour, applied voltage of 60 V_{pp}, and null voltage (“ground”) at the nodes that represent piezoelectric ceramic electrodes. Harmonic analysis is carried out to obtain electrical impedance and resonance frequencies of the piezoelectric actuator. Figure 5 shows impedance and amplitude versus frequency curves obtained for the first symmetrical vibration mode, which provides the largest amplitude values. It is possible to see the resonance and anti-resonance points in 1590 Hz and 1650 Hz, respectively.

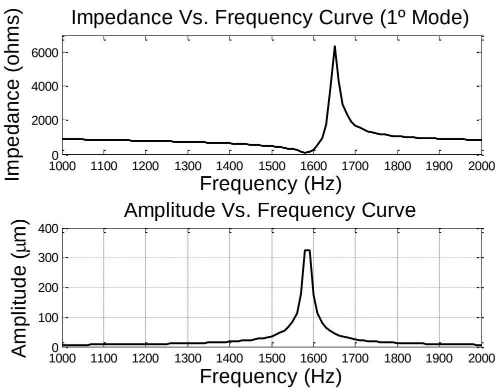

Figure 5. Impedance and amplitude versus frequency curves

For circular piezoelectric actuators symmetrical vibration mode is dominant when it is excited electrically (Hong et al., 2006). Anti-symmetrical vibration modes will appear if the excitement is mechanical only.

In the next step, sensitivity analyses are done for following adopted geometrical parameters of diaphragm pump: length of the inlet and outlet pump fittings, valve diameters, chamber height, and eccentricity in the assembly of piezoelectric actuator components. All acoustic analyses are carried out from a basic computational model, in which studied parameters are modified. Figure 6 illustrates the schematic drawing of the adopted acoustic model. The FE mesh has approximately 110,000 elements, and the boundary conditions are: fixed contour in the chamber, valves and tube; applied voltage and null voltage (“ground”) in the piezoelectric actuator electrodes; null pressure at inlet and outlet pump, and longitudinal symmetry.

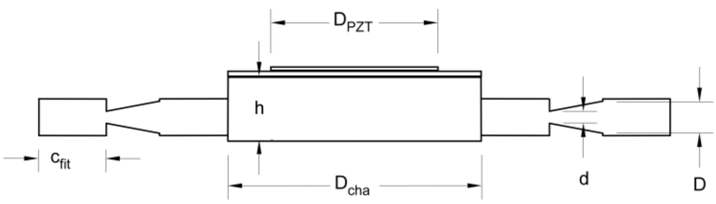

Figure 6. Basic model adopted for acoustic analyses

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Computational simulations of these analyses show that the varying in length of the pump fittings does not influence significantly the resonance frequency and amplitude of piezoelectric actuator movement. Analogous conclusion is reached for varying in valve diameter and chamber height. However, it is noticed that resonance frequency is significantly modified when eccentricity in assembly occurs. In other words, the only critical parameter for performance of piezoelectric diaphragm pump is eccentricity in assembly of components of the piezoelectric actuator. Eccentricity can occur due to deviation in bonding between the piezoelectric ceramic and the metallic plate.

Now, results obtained from sensitivity analysis around valves geometrical parameters, are shown. In these analyses, valve larger diameter (D, see Fig. 6) varies from 1.9 mm to 2.1 mm range, while small diameter (d) varies from 0.7 mm to 0.8 mm range. The valve length varies from 6 mm to 8 mm range. For each varied parameter, a fluid flow simulation is carried out to obtain an average flow rate output. To do this, simplified computational model of the piezoelectric diaphragm pump depicted in Fig. 7 is used. In this model, pump chamber assumes a cubic format, and its FE mesh has 26,756 elements. Fluid flow occurs in the horizontal direction, considering the whole body of the flow pump submerged in the water medium, that is, relative null pressures are prescribed in the nodes of inlet and outlet pump. Moreover, null displacement and velocities are imposed in the nodes which represent lateral and bottom walls of the pump chamber, and walls of valves. For this simplified model, a harmonic pressure value is imposed in the pump chamber top wall to emulate the piezoelectric actuator behavior. Density and viscosity properties of water are considered here.

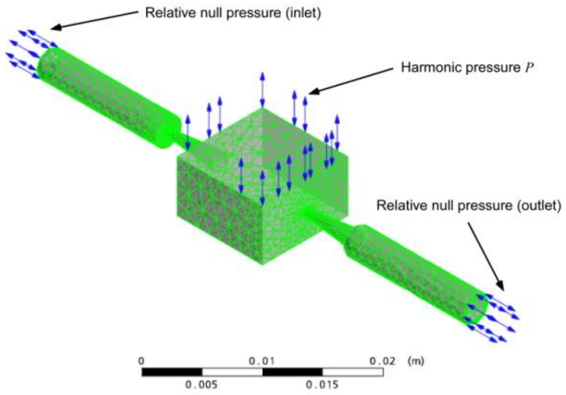

Figure 7. Simplified model for fluid flow analysis

Thus, according to results of this simplified model, it is concluded that the largest average flow rate value occurs for D=1.9mm, d=0.9mm, and considering valve length equal to 8 mm. These parameters are adopted for the complete final modeling of the diaphragm flow pump.

Figure 8 shows the complete model used in the last step of the computation simulations. This model is more detailed than the model described above, since it uses all compiled results obtained in previous simulations. The FE mesh has 42,873 elements, and boundary conditions are the same applied to simplified model. However, the piezoelectric actuator behavior is also modeled. Moving boundary conditions are specified to the faces of piezoelectric actuator, since it has an oscillatory motion. For this purpose, the ALE (Arbitrary Lagrangian-Eulerian) formulation is used, which rearranges the FE mesh at each iteration, making it coherent with the applied moving boundary conditions (Ansys, 2007).

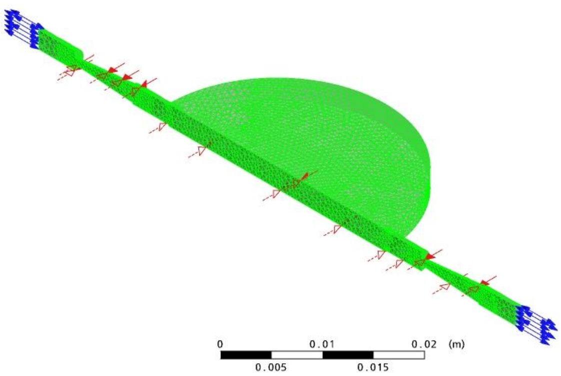

Figure 8. Diaphragm pump complete model of for fluid flow analysis

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In this model, nodal displacements and velocities of the piezoelectric actuator immerse in water, found in the harmonic analysis, can be prescribed as boundary condition in fluid flow simulation. From these results, it is possible to find a polynomial equation that reproduces approximately the oscillatory behavior of the piezoelectric actuator in their first vibration mode. Multiplying this polynomial equation by $\sin(\omega t)$, where ω is angular velocity and t is the time, one obtains a representation of the oscillatory movement of piezoelectric actuator along time. The velocity filed is found by deriving this equation. It circumvents the need of a coupled simulation system that employs both piezoelectric effect and fluid flow modeling, which would have a high computational cost.

Through this complete model, it is obtained average flow rate and static head pressure equal to 5.0 ml/min and 9.8 mmca, which will be compared with experimental values described in the next section.

4. EXPERIMENTAL RESULTS

4.1. Manufacturing prototype

An experimental prototype is built for validation purposes. Besides, a manufactured prototype is justified for checking the viability of flow pump construction, and for observing any incident phenomena not considered in the computational simulations. Figure 9 shows a view of the prototype. The materials of the pump chamber and nozzles are acrylic. The clamp and valves are manufactured in aluminum. All components are manufactured by conventional low cost cutting processes, using a CNC machine, and electro-erosion process.

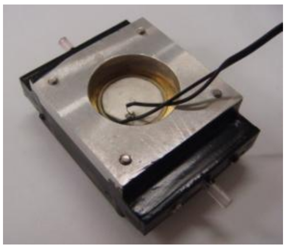

Figure 9. View of the prototype

4.2. Experimental characterization

To drive the experimental characterization of the diaphragm pump prototype, a HEWLETT PACKARD 4194A impedance analyzer is used for mapping resonance frequencies of the prototype. Piezoelectric actuator is actuated by an amplifier circuit INOVEO FG1000 (designed and built to this experiment).

Knowing the prototype resonance frequencies, the flow rate evaluation of the piezoelectric diaphragm pump is performed. The experimental setup used in the simulations consists of associating a glass pipe of circular section, with known area and length, in series configuration with the pump inlet and to measure the time that the water takes to cross the glass pipe length and, then, the flow rate at pump outlet is calculated (Lima et al., 2009). A colored pigment is injected at inlet pump to allow the flow visualization. As diaphragm flow pump must operate out of the water reservoir, a system of connected vessels is necessary, as illustrated in Fig. 10. Thus, the fluid is pumped from small reservoir to large reservoir by the prototype, while a linkage tube maintains water surface level aligned in both reservoirs.

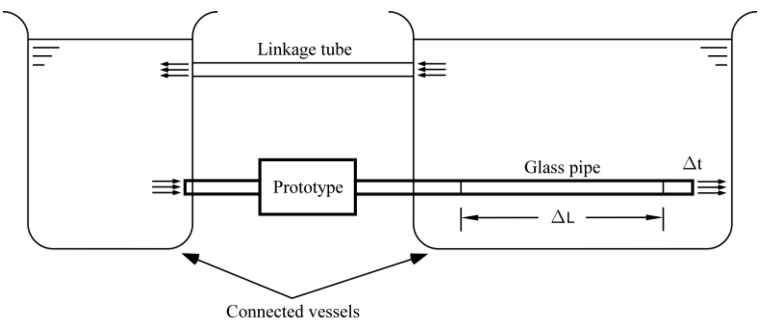

Figure 10. Flow rate experimental measurement

To evaluate the static head pressure produced by the diaphragm pump, the prototype is positioned as shown in Fig. 11. Before diaphragm pump is turned on, it is observed that the water-levels in the vessels and in the pump outlet duct are aligned. Thus, the water-column (static head pressure) generated in outlet duct is measured (ΔP).

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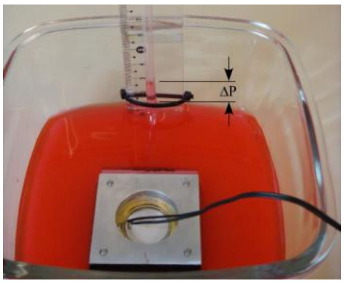

Figure 11. Pressure experimental measurement

Through experimental tests, it is noticed a maximum flow rate and static head pressure values equal to 2.5 ml/min and 18 mmca, at first vibration mode resonance frequency.

5. CONCLUSION

A methodology for development of a low cost piezoelectric diaphragm flow pump (valve-less type), using finite element modeling and experimental prototype, is presented. Two steps of sensitivity analyses are carried out to indentify the best geometrical parameters of diaphragm flow pump. It is concluded that resonance frequency is significantly modified when eccentricity in assembly occurs, then, a precise assembly between piezoelectric ceramic and metallic plate is fundamental to assure better performance of the diaphragm pump. By comparing the results obtained from computational simulations and experimental tests, it is possible to conclude that computational simulations provide results whose magnitude are not too close to the experimental results. These computational results are preliminary and damping factor has not been considered yet. This piezoelectric diaphragm pump has potential miniaturization to be applied in several applications, thus, this aspect will continue being studied by analyzing the physical phenomena to validate the device design.

6. ACKNOWLEDGEMENTS

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