OPTIMIZATION OF OSCILLATORY FLOW PUMP USING BIMORPH PIEZOELECTRIC ACTUATORS IN PARALLEL MODE

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Abstract. *Precision flow pumps have been widely studied over the last three decades. They have been applied in the areas of Biology, Pharmacy and Medicine in applications usually related to dosage of medicine and chemical reagents. In addition, thermal management solutions for electronic devices have also been recently developed using these kinds of pumps, offering better performance with low noise and low power consumption. In a previous work was presented the working principle of a pump based on the use of a bimorph piezoelectric actuator inserted in a fluid channel to generate flow. In this work, a novel configuration of this piezoelectric flow pump is presented, that consists of a flow pump using two or more bimorph piezoelectric actuators in parallel configuration. This configuration was inspired on fish swimming modes. The complete cycle of pump development was conducted, consisting in designing, manufacturing, and experimental characterization steps. The Response Surface Method (RSM) was used to maximize the flow rate. Comparisons among numerical and experimental results were made to validate the computational results and improve the accuracy of the implemented models.*

Keywords: *Microfluidics, Flow Pump, Bimorph Piezoelectric Actuator, CFD, Optimization*

1. INTRODUCTION

The development of precision flow pumps, with small power consumption and small volume of fluid displacement, has been widely investigated (Laser and Santiago, 2004). They have been applied in industry as essential components in systems for cooling electronic devices (Singhal, Garimella and Raman, 2004), solutions for reagent and medicine dosage (Pickup et al., 1978; Teymoori and Abbaspour-Sani, 2005) and biological fluid pumping systems (Andrade et al., 1996).

Many of the new principles in flow pumps development are based on the use of piezoelectric actuators (Yoo, Hong and Cao, 2000; Burmann, Raman and Garimella, 2003; Açikalin, Raman and Garimella, 2003). These actuators present some advantages in relation to other solutions, for example, miniaturization potential, lower noise generation, and fewer numbers of moving parts. One of the examples of piezoelectric flow pump is the ultrasonic pump of Bar-Cohen (Bar-Cohen and Chang, 2001), which uses stators piezoelectrically actuated, that generate a propagating wave that moves the fluid. The movement obtained in this example is similar to the peristaltic movement, which is observed in the human esophagus.

Another example of piezoelectric pump is the diaphragm pump, which uses a piezoelectric actuator to move a membrane, having the flow direction controlled by check valves. This pump has been investigated by many researchers, such as Koch et al. (1998) and Ullmann et al. (2001).

The powerful microchips inside the modern electronic equipment require each day the use of more advanced cooling techniques, however, the traditional devices used for this purpose, such as fans and heat exchanger fins, became inefficient to dissipate the heat generated by these modern components. Thus, among the new technological solutions for overcoming this problem, it can be cited the application of precision flow pumps used in closed liquid circulation systems inside small heat exchangers (Singhal, Garimella and Raman, 2004). A principle, which is based on the use of bimorph piezoelectric actuator, has been applied to a piezoelectric fan for cooling purposes using air as coolant. This device has been studied by many researchers (Yoo, Hong and Cao, 2000; Burmann, Raman and Garimella, 2003; Açikalin, Raman and Garimella, 2003; Açikalin et al., 2004; Kim, Werely and Chun, 2004; Basak, Raman and Garimella, 2005).

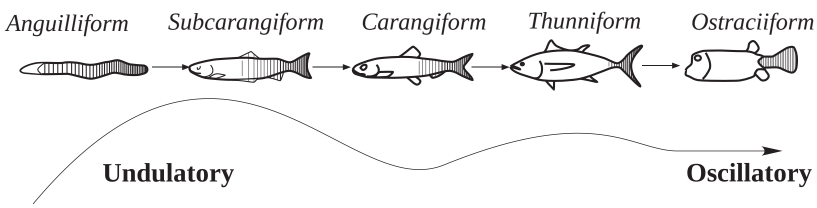
In previous works (Pires et al., 2006; Vatanabe et al., 2007), the working principle of a flow pump based on the use of a bimorph piezoelectric actuator inserted in a fluid channel to generate flow was presented. In this work, novel configurations of piezoelectric flow pumps based on the use of n bimorph piezoelectric actuators in parallel configuration has been studied and it is presented.

In the next sections of this paper, the development of the piezoelectric flow pump is presented, including the proposed principle, the use of piezoelectric actuators, the use of the software ANSYS^{TM} for computational simulations, as well as the Surface Response Method (RSM). Finally, the latest computational results are shown.

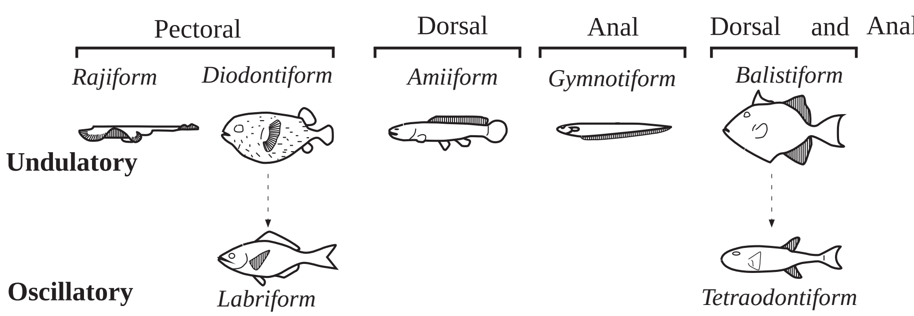
2. PRINCIPLE

The pumping principle proposed in this work aims at reproducing a phenomenon seen in nature: a swimming fish motion. Studies about this topic have been carried out by researchers such as Triantafyllou et al. (1993), Sfakiotakis et al. (1999) and Videler et al. (1999).

Sfakiotakis et al. (1999) presented a classification for fish families appeared during the evolution, according to their propulsors. Most fish have propulsion generated by moving their bodies or caudal fin (Fig. 1(a)). Other fish swim due to movements of their median and/or paired fins (dorsal, anal, pectoral or pelvic), as it can be seen in Fig. 1(b).



(a) Locomotion by body and/or caudal fin movements.



(b) Locomotion by median and/or paired fins.

Figure 1. Fish swimming modes. Shaded areas contribute to locomotion.

In the first group, showed in Fig. 1(a), there are fish that present undulatory motion with a propagating wave formation through their bodies such as eels and lampreys (anguilliform swimmers). Other families exhibit oscillatory motion, shaking their bodies and caudal fins, moving forward without a propagating wave formation such as the ostraciiform swimmers. There are also other fish that present a combination of both movements, as it can be seen in Fig. 1(a).

The wake left by fish that swims due to undulatory and/or oscillatory motion of their bodies and caudal fins consists in an array of trailing discrete vortices of alternating signal (Sfakiotakis et al., 1999), as it can be seen in Fig. 2(c). This vortex street has reversed rotational direction compared to the Karman vortex street (Fig. 2(a)), which produces drag around bodies placed in a free stream (Sfakiotakis et al., 1999; Triantafyllou et al., 1993). Flow generation in the opposite direction can be observed, between the vortices in Fig. 2(c).

The fish makes an oscillatory motion, swinging its body and tail to move forward. What would happen if one holds the fish while it tries to move? A fluid motion is observed, therefore the fish acts as a flow pump. This phenomenon is similar to a thin plate in oscillatory motion inside a fluid environment, showed in Fig. 3. This fact is important because the vortex interaction results in a flow rate to the right side due to the action and reaction principle.

Based on this phenomenon, Pires et al. (2006) studied a miniature flow pump based on the use of a bimorph piezoelectric actuator excited in its second vibration mode, achieving flow rate of approximately 40 cc/min.

Vatanabe et al. (2007), studied another miniature flow pump based on the use of two bimorph piezoelectric actuators inside the same channel, excited in its second vibration mode, achieving flow rate of approximately 90 cc/min (computational).

The aim of this work is the optimization study of a oscillatory flow pump to achieve higher flow rates than the flow pumps cited above, based on the use of n bimorph piezoelectric actuators in parallel configuration, inside the same channel. This configuration is illustrated in Fig. 4.

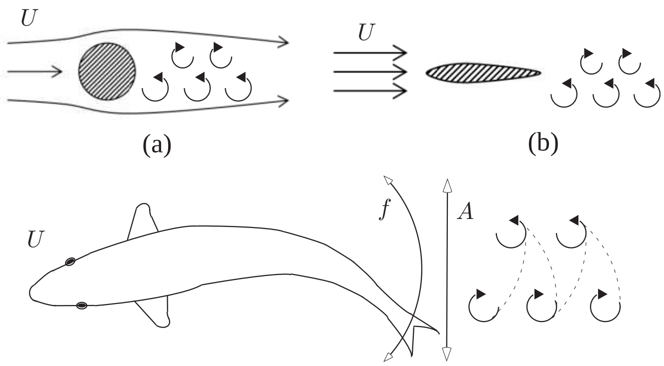


Figure 2. Karman street for a cylinder (a) and for a wing profile (b). Wake left by a fish swimming (c). The formation of an array of trailing discrete vortices of alternating signal is observed.

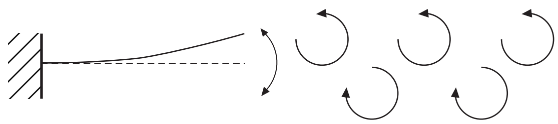


Figure 3. Vortices generated by a thin plate in oscillatory motion.

The parameters analyzed consist in the distance between both actuators (H$_{gap}$), the channel height (H$_{channel}$), the inlet entrance (H$_{inlet}$).

According to micropumps classification presented by Laser and Santiago (2004), this pump is ought to be considered a "dynamic pump", i.e. a pump which continuously adds energy to the working fluid in a manner that also increases its momentum.

3. THEORETICAL CONCEPTS

3.1 Piezoelectric Actuators

A piezoelectric material (PZT) is capable of converting electric energy into mechanical energy and vice-versa. The constitutive equations for piezoelectric effects are:

$$\boldsymbol{\tau} = \mathbf{c}^E\mathbf{S} - \mathbf{e}^t\mathbf{E} \tag{1}$$

$$\mathbf{D} = \mathbf{e}\mathbf{S} + \boldsymbol{\varepsilon}_D^S\mathbf{E} \tag{2}$$

where: $\boldsymbol{\tau}$ = stress tensor; $\mathbf{e}$ = piezoelectric tensor; $\mathbf{S}$ = strain tensor; $\boldsymbol{\varepsilon}_D^S$ = electric permissivity tensor for constant strain; $\mathbf{D}$ = electric displacement vector; $\mathbf{c}^E$ = stiffness tensor for constant electric field; $\mathbf{E}$ = electric field vector.

A bimorph piezoelectric actuator is an electromechanical flexible actuator mounted as a clamped beam with a free end. Its construction consists of a metallic plate allocated between two piezoelectric ceramic plates. When an electric voltage is applied to the ceramic, the metallic plate is deformed proportionally to the applied voltage. Figure 5 shows the combination of a bimorph (PZT/metal/PZT) that allows such displacements once the piezoelectric ceramics operate in opposite modes (in series or in parallel). In other words, when a piezoceramic is expanded the other is compressed, bending the actuator. A bimorph actuator with dimensions described ahead shows displacements around 1 mm, however with very low forces (Pires et al., 2006). Its typical response can be found around 10 μm/V in static regime. Operating in its resonant frequency a response of 50 μm/V is to be measured. Fig. 5 presents the main geometric characteristics of the actuator used in this work.
where $\mathbf{L}_{total}$ = 40 mm; $\mathbf{L}_{PZT}$ = 35 mm; $\mathbf{L}_{clamp}$ = 1 mm; $\mathbf{e}_{metal}$ = 0,2 mm; $\mathbf{e}_{PZT}$ = 0,2 mm. The boundary conditions represent a clamped beam with a free end.

3.2 Finite Element Method (FEM)

The use of a Finite Element Method (FEM) tool is justified since we are dealing with a complex problem whose analytical solution is unfeasible. The use of computational models also allows the evaluation of a given system behavior reducing the prototype construction costs.

For the piezoelectric pump simulations, the ANSYS^{TM} finite element software has been used. In its vast library of elements covering a wide range of physical phenomenons the FLUID141 element can be found, which is applied for bidimensional fluid simulations. This element has options of 3 or 4 nodes and has 5 degrees of freedom (DOFs) in

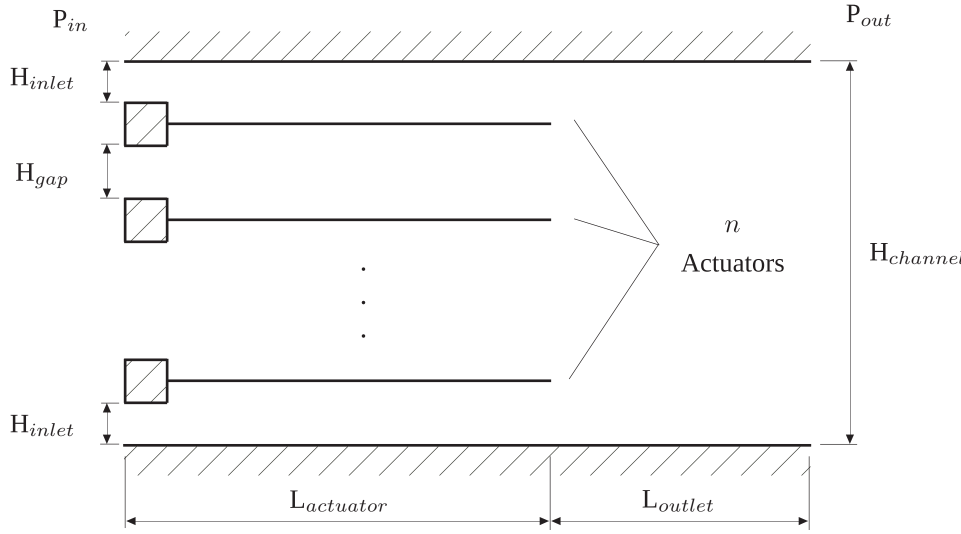


Figure 4. Piezoelectric flow pump with actuators in parallel configuration.

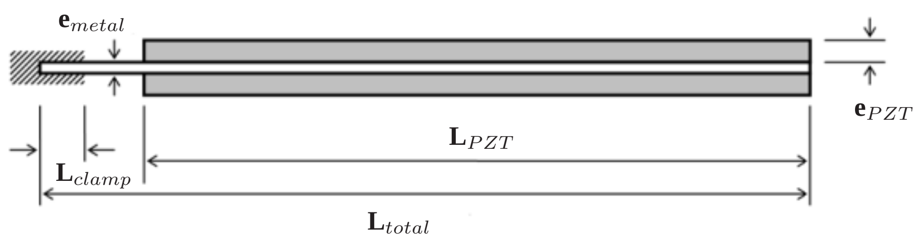


Figure 5. Geometric characteristics of the piezoactuator.

each node: 'x' and 'y' velocity components, pressure, temperature and kinetic energy. In the simulation, the software essentially solves the mass conservation, momentum and energy sets of equations (ANSYS, 2003).

Problems involving fluid simulation commonly deal with moving boundaries. In this case, the actuator has an oscillatory motion. Therefore, the domain of this system changes as time passes and the finite element mesh must be changed to accommodate such conditions. For this purpose the ALE ("Arbitrary Lagrangian-Eulerian") formulation, implemented in the ANSYS^{TM} software, is used and it allows us to apply moving boundary conditions to the system. The finite element mesh is changed during the simulation, making the problem solution close to reality.

For the simulation, displacements and velocities on the moving boundaries must be set. The ALE formulation is responsible for rearranging the mesh at each iteration, making it coherent with the imposed conditions. Throughout the simulation a wide range of parameters can be obtained, such as pressure and velocity, the main variables to be evaluated in this case.

3.3 Response Surface Method (RSM)

The Parametric Optimization Method is used in this work to obtain the configuration of the bilaminar actuators that maximizes the flow rate. Due to the complex behavior of the fluid, it is difficult to describe analytically the objective function and its gradients in terms of the design variables. Therefore, it is adequated to use the Response Surface Method (RSM) (Myers and Montgomery, 1995), associated with the Parametric Optimization procedure. The Response Surface Method (RSM) combines techniques of curve fitting by regression with optimization using the obtained curves. The RSM initial data are values of the objective function at some design configurations, in this work obtained by numerical experiments. Using enough number of those values, which depends on the number of design variables and the type of function used in curve fitting, the RSM defines a surface that approximates the behavior of the objective function inside a certain design domain.

In this work, second order polynomials are used as fitting curves. Thus, the response surface $(y(x_1, x_2)$ can be described by Eq. (3), in terms of the design variables:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1^2 + \beta_4 x_2^2 + \beta_5 x_1 x_2 \tag{3}$$

Defining new variables x_3, x_4 and x_5 as $x_3 = x_{12}$, $x_4 = x_{22}$, and $x_5 = x_1 x_2$, Eq. (3) can be written as a linear regression [9].

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 \tag{4}$$

The coefficients β_i's are determined through the least square error method. Using two design variables and n experiments the coefficients are calculated using Eq. (4):

$$\beta = (\mathbf{X^T X})^{-1}\mathbf{X^T Y} \tag{5}$$

where:

$$\mathbf{Y} = \left\{ \begin{array}{c} y_1 \\ y_2 \\ \vdots \\ y_n \end{array} \right\}, \mathbf{X} = \begin{bmatrix} 1 & x_{11} & x_{21} & \dots & x_{51} \\ 1 & x_{12} & x_{22} & \dots & x_{52} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_{1n} & x_{2n} & \dots & x_{5n} \end{bmatrix}, \beta = \left\{ \begin{array}{c} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_4 \\ \beta_5 \end{array} \right\} \tag{6}$$

Once a second order polynomial that approximates the objective function behavior is obtained, the optimal configuration can be obtained using a variety of mathematical procedures. With the objective of applying tools that are common in the industrial environment the MATLAB^{TM} *fmincon* function was used. The *fmincon* finds a function optimal value inside a given feasible design domain.

4. COMPUTATIONAL RESULTS

Vatanabe et al. (2007) studied a flow pump operating with water, using two piezoelectric bimorph actuators inside the same channel. The model simulated is similar to Fig. 4, considering $n = 2$. The parameters of simulation is showed in Table 1.

Table 1. Parameters for pump simulation.

Frequency:	278 Hz
Amplitude:	0.3 mm
Channel width:	20.0 mm
Channel height ($H_{channel}$):	15.0 mm
Inlet height (H_{inlet}):	4.5 mm
Gap height (H_{gap}):	2.0 mm
Actuator length ($L_{actuator}$):	36.0 mm
Outlet length (L_{outlet}):	10.0 mm
Inlet and outlet pressure:	1 atm

Each actuator is excited with a sinusoidal wave excites . The advantage of this configuration are the vortex interaction generated by each actuator oscillatory motion. As a result of this interaction two vortex streams are generated. However, there is a difference when the actuators oscillate in phase or out of phase (Vatanabe et al., 2007). In the first case, in phase motion, the vortex generated by the actuators appear intercalated in the middle of the channel contributing to flow generation. In the second case, the vortices present a vertical alignment generating a flow rate with less intensity than that one obtained in the first case.

In order to optimize the use of the vortex for flow generation it is necessary to optimize actuators position, i.e., to find the best values for H_{inlet} and H_{gap}. In this case (n = 2 actuators), the channel height was fixed at $H_{channel} = 15mm$ and the variables H_{inlet} and H_{gap} are set in pairs, so it is not possible to obtain a surface response.

The highest flow rate obtained in steady state varying these two variables is approximately 90.0 cc/min, with dimensions of $H_{inlet} = 4.5mm$ and $H_{gap} = 2.0mm$. Therefore, by using two piezoactuators inside the same flow pump is possible to reach higher flow rates than using two different pumps in parallel configuration with only one actuator in each one (Pires et al., 2006). The obtained flow rate in the second case would be 80.0 cc/min approximately, as it can be seen in Fig. 6.

Based on these results, we decided to simulate a new model using three bimorph actuators in parallel mode, inside the same flow pump, to verify if there is an optimum number of actuators vibrating in parallel mode. The parameters of simulation is showed in Table 2.

The channel height ($H_{channel}$) was set free and some values were chosen for pump inlets (H_{inlet}) and the gaps between the actuators (H_{gap}). A total of 29 cases were simulated, combining the values of H_{inlet} and H_{gap}.

After all the simulations, the flow rate surface response was obtained using the Response Surface Method (RSM), as described in 3.3in function of these two variables, which can be seen in Fig. 7.

Fig. 7 shows that flow rate is proportional to H_{inlet} and H_{gap}, achieving values higher than 260 cc/min. Therefore, there is a tradeoff between the channel height ($H_{channel}$) and the flow rate generated by three bimorph actuators.

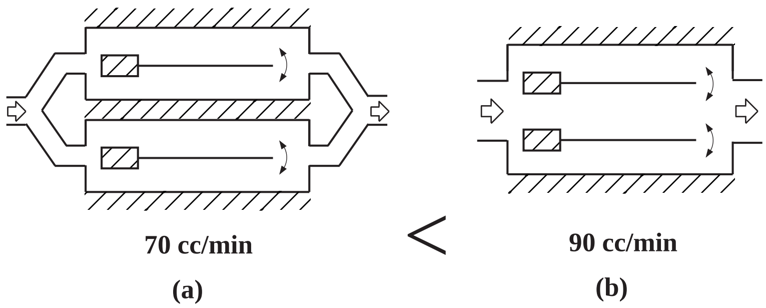


Figure 6. Two actuators in parallel configuration inside the same pump generate higher flow rate. (a) Two flow pumps with only one actuator in each one, (b) Flow pump with two actuators in parallel configuration.

Table 2. New parameters for pump simulation with three bimorph actuators.

Frequency:	278 Hz
Amplitude:	0.3 mm
Channel width:	20.0 mm
Channel height ($H_{channel}$):	13.2 to 17.6 mm
Inlet height (H_{inlet}):	2 to 3 mm
Gap height (H_{gap}):	1.6 to 2.8 mm
Actuator length ($L_{actuator}$):	36.0 mm
Outlet length (L_{outlet}):	10.0 mm
Inlet and outlet pressure:	1 atm

5. MANUFACTURING AND EXPERIMENTAL CHARACTERIZATION

In this section, the prototype manufacturing and experimental methods that are used for the prototype characterization are described.

A schematic drawing of the piezoelectric pump driver apparatus is shown in Fig. 8. An AGILENT 33120A function generator and an AGILENT E3649A DC power supply were applied to drive the experimental prototype, as well as an amplifier circuit that was designed and built to this work.

The experimental methods used in this work are presented in the next sections.

5.1 Resonant frequencies measurement

To determine the piezoactuator resonant frequencies inside the prototype channel, under the water, the experimental electrical impedance ("Ohms") versus frequency (Hertz) curves are obtained for a frequency range from 100 Hz to 1 kHz. A HEWLETT PACKARD 4194A impedometer analyzer was used for this purpose. The obtained curves were acquired in a computer using a data acquisition function that was implemented in MATLAB^{TM}.

5.2 Flow rate characterization

Knowing the prototype resonant frequencies, the next tests were performed for experimental flow rate characterization to evaluate prototype performance. The flow rate ("cubic centimeters/minute") versus frequency ("Hertz") curve and the flow rate ("cubic centimeters/minute") versus applied voltage ("Volts peak-to-peak") curve were obtained.

The method consists in associating a glass pipe of circular section, with known area and length, in series configuration with the piezoelectric pump inlet, as shown in Fig. 9. Colored water, due to the application of a red pigment, is injected through the pipe inlet. At this moment the prototype is turned on, the flow (before crossing the pump channel) presents a laminar velocity profile, whose the maximum velocity is calculated by measuring time "Δt" that the water takes to cross the known length "Δl". Due to the fact that there is a laminar flow inside a tube, the profile average velocity is half of the calculated maximum velocity. Knowing the average velocity and the pipe area, it is possible to calculate the flow rate "Q", for the same pressure "P" at the pipe inlet and pump outlet and for a defined sinusoidal signal with known frequency and applied voltage.

Firstly, the flow rate versus frequency curve is obtained, keeping the same applied voltage value. After this, for some fixed frequency values, the experimental flow rate versus applied voltage curve is obtained.

The experimental tests, according to this method, is performed to evaluate the piezoelectric performance in applica-

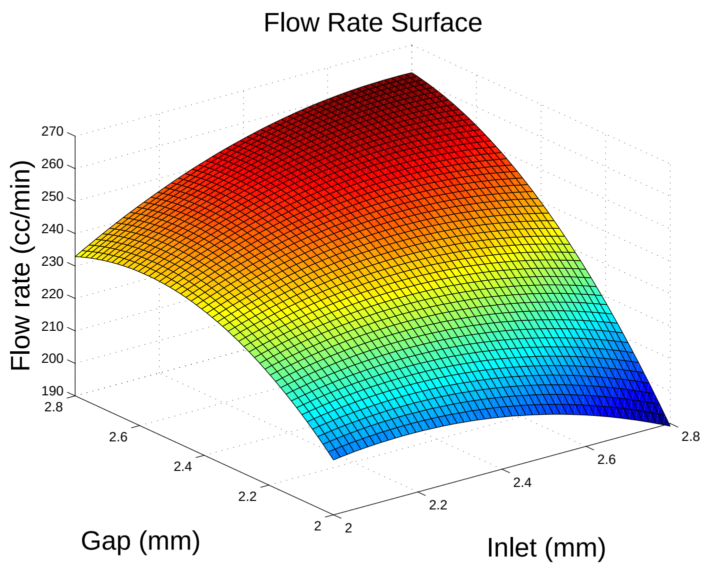


Figure 7. Flow rate surface obtained using the Response Surface Method.

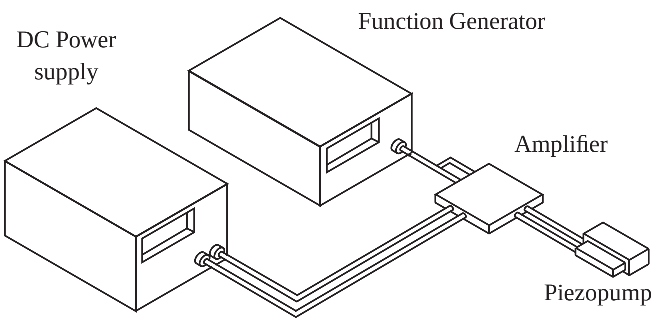


Figure 8. Piezoelectric pump driver apparatus.

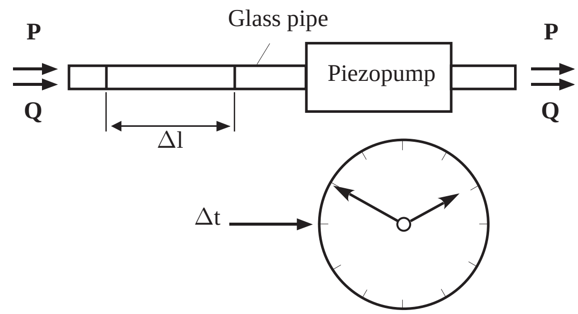


Figure 9. Apparatus for experimental flow rate characterization.

tions involving closed liquid circulation (due to the fact that the pressure is the same at the pump inlet and outlet).

6. EXPERIMENTAL RESULTS

During the computational simulation of a flow pump with three actuators, it was decided to design and build a pump prototype with two actuators in parallel configuration, to validate the computational results described in the section 4.

The best case of maximum flow rate obtained through the computational simulations has the dimensions $H_{inlet} = 4.5mm$ and $H_{gap} = 2mm$. The clamps have thickness equal to 2 mm. Both actuators are excited in phase. A scheme with the dimensions as well as the prototype design are shown in Fig. 10 and Fig. 11.

An impedometer analyzer is applied to determine the actuators resonant frequencies in air and water after the prototype construction. Firstly, each actuator is tested, separately; after this, the two actuators in parallel configuration are tested. The obtained frequencies are described on Table 3.

Table 3. Piezoelectric actuators experimental test (impedometer).

Condition	1st Mode	2nd Mode
Air	115 and 140 Hz	1050 and 1120 Hz
Water	-	430 and 430 Hz

It was not possible to determine the first mode in water condition because the impedometer range begins at 100 Hz.

Figures from 12 to 13 describe the impedance versus frequency curves inside water. The resonant frequencies obtained for the prototype in water are 41 Hz for first vibration mode and 416 Hz for second mode. Since the impedometer analyzer range begins at 100 Hz, the first vibration mode was determined during the flow rate characterization tests through the frequency in which a local maximum flow rate was observed.

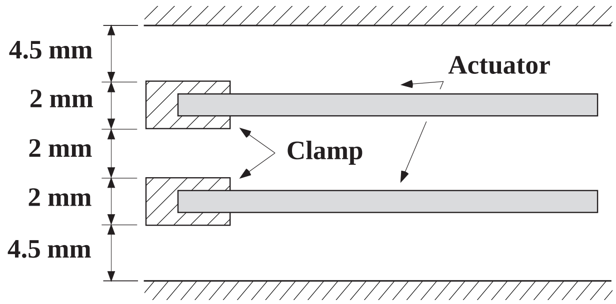


Figure 10. Prototype scheme.

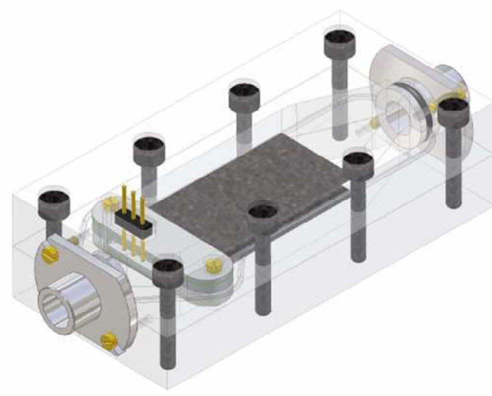


Figure 11. Prototype design. Isometric view.

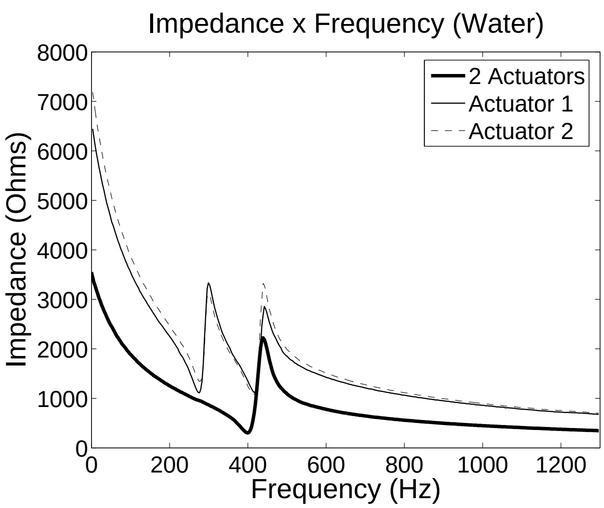


Figure 12. Impedance versus frequency curve in water.

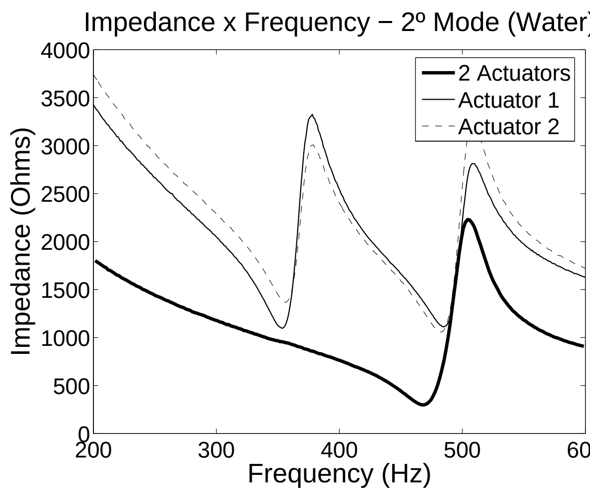


Figure 13. Impedance versus frequency curve in water. Detail for second mode.

The prototype generates a smaller flow rate for first vibration mode than calculated one. This flow rate can not be measured because of the flow rate characterization apparatus presents load loss. However, in its second vibration mode (416 Hz), it is possible to observe a flow rate of approximately 44.0 cc/min.

7. CONCLUSIONS AND FUTURE WORK

Based on the experimental tests, the prototype with two actuators in parallel configuration did not match with the computational results, since the flow rate experimentally observed was 44 cc/min which is smaller than the computational results (90 cc/min). A hypothesis for this phenomenon is the influence of tridimensional vibrational modes of the actuators which might be inverting the flow direction. However, computational simulation shown that is possible to reach higher flow rates by using two piezoactuators inside the same flow pump than by using two different pumps (Pires et al., 2006) in parallel configuration with only one actuator in each one.

Computational results showed that using three bimorph actuators in parallel configuration inside the same flow pump generates higher flow rates than using one or two bimorph actuators. Therefore, new computational analysis will be performed considering more than three bimorph actuators to maximize the flow rate.

As a future work, new configurations of oscillatory flow pumps based on the use of bimorph piezoelectric actuators will be studied such as series configurations and others using both series and parallel configurations of actuators inside the same flow pump.

8. ACKNOWLEDGMENTS

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