MECHATRONIC PUMP CHARACTERIZATION: THE "MECH-PUMP"

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Abstract. *Flow pumps, in addition to their classical applications in engineering, have been acting as important instruments in areas such as Biology, Pharmacy and Medicine. A new principle for fluid pumping have been studied inside the Department of Mechatronic Engineering and Mechanical Systems of the Polytechnic School at University of Sao Paulo. The current design uses a bimorph piezoelectric actuator inserted in a fluid for flow generation. The main objective of this work is the characterization of this pump setup through the simulation using commercially available software ANSYS® and prototype construction. Computational simulations include plotting of characterization curves, sensitivity studies and optimization process to predict a better combination of parameters for this pump. Prototype characterization tests have been carried out with support of IPT (Technological Research Institute) and Dante-Pazzanese Institute of Cardiology, and it includes load-loss against flow rate and flow rate against frequency graph plotting. Comparisons between numerical and experimental results are also made.*

Keywords*: piezoelectric, micropumps, bimorph, CFD, optimization, finite element*

1. Introduction

The development of precision flow pumps, with small power consumption and small volume of fluid displacement, have been widely investigated. Bioengineering is one of the most enthusiastic areas for this sort of equipment, for application in blood pumping or medication and reagent dosage such as continuous insulin injection in diabetic patients, eliminating peaks and valleys of this dosage common in the usual approach. Other applications could be found for these pumps, such as, cooling applications in electronic devices.

New principles have been investigated as a way to overcome the present matters found in the traditional biological fluid pumping techniques, the most relevant of which could be the death of microorganisms and cells in the fluid during the process, caused by the high pressure or even the turbulence generated in the flow. In Brazil, for instance, the Spiral Pump from Andrade et al (1996), investigated and developed by Dante Pazzanese Institute of Cardiology together with Baylor College of Medicine (Houston, Texas) for applications in bypass surgeries, combines both radial and axial fluid pumping principles.

Moreover, computational simulations have been used to predict hemolisys indices (death of hematias). This kind of activity have been carried out by many researchers, Yano et al (2003), Okamoto et al (2003) and Song et al (2003). In the present blood pumping techniques hemolisys indices are relatively high, which is highly undesirable. New techniques seek a minimization of this problem.

Many of the new principles in flow pumps development are based on the use of piezoelectric actuators. One of the examples of piezoelectric flow pump is the ultrasonic pump of Bar-Cohen; Chang (2001), which uses stators made of an elastic material which are piezoelectrically actuated, generating a propagating wave that moves the fluid.

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, Koch et al (1998) and Ullman; Fono; Taitel (2001). One last example of piezoelectric pump is shown by Kar et al (1998), which is based on a mechanism similar to a syringe, that utilizes a piezoactuator to control its dosage.

The present work aims at the investigation of a new pump configuration, which will be described in the following section, through finite element modeling and prototype construction.

A similar principle have been studied by Açikalin et al (2003, 2004), Basak; Raman; Garimella (2005), Kim; Wereley; Chun (2004) and Yoo; Hong; Cao (2000), for cooling purposes, using air as coolant.

More details about alternative methods of fluid pumping can be found in Laser; Santiago (2004). In this article, the authors dedicated themselves to a vast investigation through the principles used in micropumps, aiming both qualitative and quantitative comparison among the various pumps researched and developed in the world.

Laser; Santiago (2004) analyze parameters such as flow and pressure rates and also scale factors, thermodynamic efficiency and 'self-pumping frequency', a parameter that considers the maximum flow achieved by a pump compared to its constructive size.

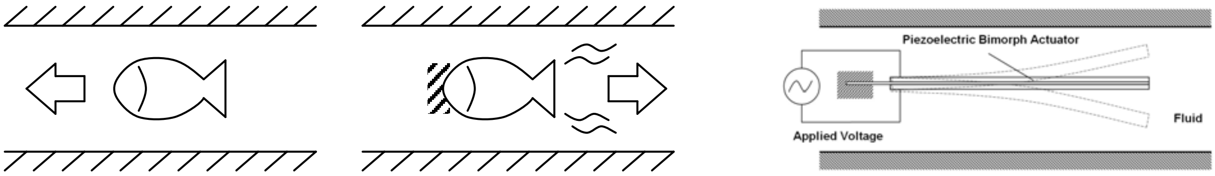
The pumps might be classified Laser; Santiago, (2004) in two large groups: 'displacement pumps' and 'dynamic pumps'. The first group includes the so called 'reciprocating pumps', the most known of which are the 'diaphragm pumps'. In this same group one may find the rotary and aperiodic pumps. In the other group centrifugal, electrohydrodynamics, electroosmotics, magnetohydrodynamics, acoustic streaming/ultrasonic and other types of pumps are to be found.

In the next sections the proposed principle, the use of a piezoelectric actuator and the use of the software ANSYS® for computational simulations will be discussed. Finally, the latest results will be shown, including numerical against experimental data comparison.

2. Principle

The principle of pumping proposed in this work aims at reproducing a phenomenon seen in the nature: a swimming fish motion. Studies about this topic have been carried out by researchers like Sfakiotakis; Lane; Davies (1999) and Videler; Müller; Stamhuis (1999).

Figure 1(a) illustrates this principle.



a) b)

Figure 1. Principle of the flow pump proposed (a) and bimorph piezoelectric actuator (b)

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 to be observed, therefore the fish acts as a flow pump.

The proposal for the piezoelectric pump is to use a bimorph piezoelectric actuator to reproduce this oscillatory behavior of the fish, by putting an oscillating body in a fluid environment for flow generation. This actuator has a plate shape and, when excited with an AC voltage, reproduces the desired motion [Fig.1(b)].

According to Laser; Santiago (2005), this pump is ought to be considered a 'dynamic pump', although no subdivision to classify it is to be found at the present moment.

3. Theoretical Aspects

3.1. Piezoelectric Actuators

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

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

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

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 functionality is based on the bimetallic thermostat, with a metallic plate allocated between two piezoelectric ceramic pieces. When an electric voltage is applied to the ceramic, the metallic plate is deformed proportionally to the applied voltage. Fig. 1(b) 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 ceramic is expanded the other is compressed, bending the actuator. A bimorph actuator shows displacements around 1mm, however with very low forces. Its typical response can be found around 10μm/V in static regime. Operating in its resonant frequency a response of 50 μm/V is to be measured.

3.2. Finite Element Method (FEM)

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

For the piezoelectric pump simulations, the ANSYS® finite element software is being used. In its vast library of elements covering a wide range of systems 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 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.

Problems involving fluid simulation commonly deals 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® software, is used.

The ALE formulation allows us to apply moving boundary condition to the system. The finite element mesh is changed during the simulation, making the problem solution close to reality.

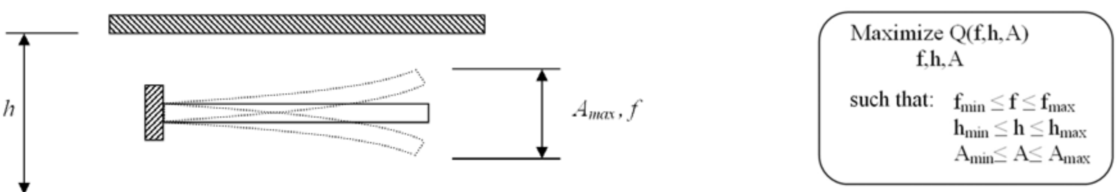
For the simulation, displacements and velocities on the moving boundaries must be set. The ALE formulation is responsible for rearranging the mesh at each iteration, making it coherent with the imposed conditions. Throughout the simulation a wide range parameters can be measured, such as pressure and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

3.3. Optimization

Engineering problems commonly deals with multiple design variables. The complexity to find optimum values can be analyzed. Numerous design variables could be defined for the piezoelectric pump, such as frequency of oscillation, height of the duct, amplitude of oscillation, length of the actuator and area section in the inlet and outlet of this pump. Initially, it will be considered only three design variables (frequency of oscillation, height of the duct and amplitude of oscillation). In the case of a CFD (“Computational Fluid Dynamics”) simulation, the computational time can easily reach a magnitude of 10^4s. Supposing each variable to assume twenty previously established values, mapping all the possibilities to find the best combination of parameters would take $20^3.10^4=8.10^7$s ~ 2.5 years.

The solution for this problem is the use of a rational search method through numerical algorithms that can drastically reduce the time until an optimal solution is achieved.

The formulation of an optimization problem involves the concepts of design variables, objective function, constraints and feasible domain. Design variables are the ones which can be modified to optimize the system. In this case, the design variables, mentioned above, can be seen in the Fig. 2(a).



a) b)

Figure 2. Pump design variables (a) and optimization problem (b)

The objective function for this optimization problem is to maximize the average flow ratio (Q) in the duct. Constraints are related to the imposed limitations to obtain the desired results. In this case, for instance, the amplitude of vibration has to be less than the height of the duct for physical coherence. Therefore, the optimization problem is defined as in Fig. 2(b) above.

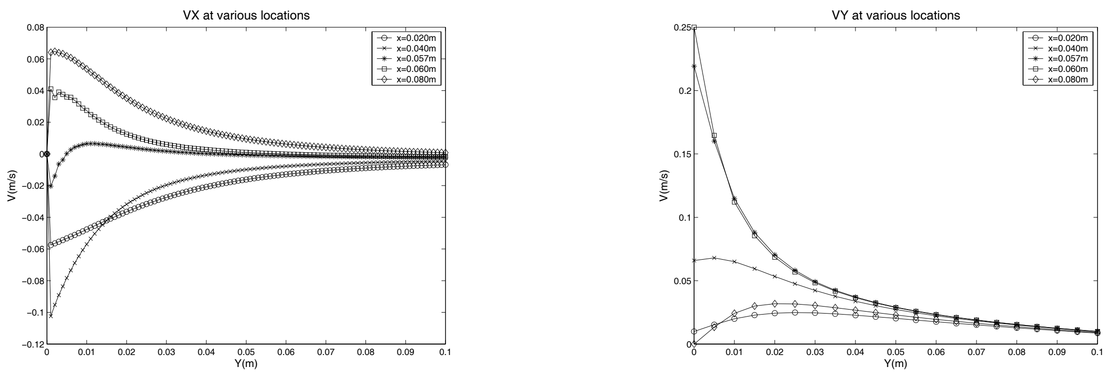
This optimization problem is solved by using the Altair Hyperstudy software.

4. Results

4.1. Computational Results

In this section the computational results are presented.

The first step taken for the computational simulations was a comparison of ANSYS® results with a literature example (Açikalin; Raman; Garimella, 2003). A principle similar to the one proposed here is investigated through numerical simulation and experiments on a half domain of a bimorph actuator surrounded by air. The results are shown below:

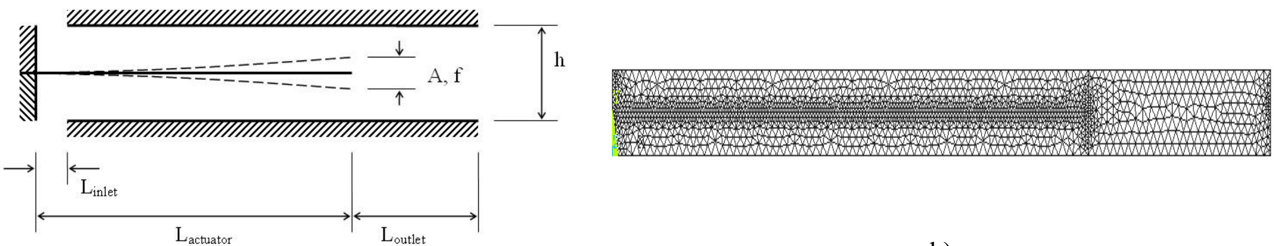


a) b)

Figure 3. Computational simulation results

Figure 3(a) and Fig. 3(b) show the ‘x’ and the ‘y’ velocity component respectively obtained through the use of ANSYS®. A very good agreement is noticed when comparing the results with results shown by Açikalin, Raman, Garimella (2003).

The next step was the simulation of the pump itself, using the parameters of the prototype built. Due to constructive constraints, some modifications in the original idea were made. The following scheme [Fig. 4(a)] represents the side view of the piezoelectric pump.



a) b)

Figure 4. Scheme and mesh of the piezoelectric pump

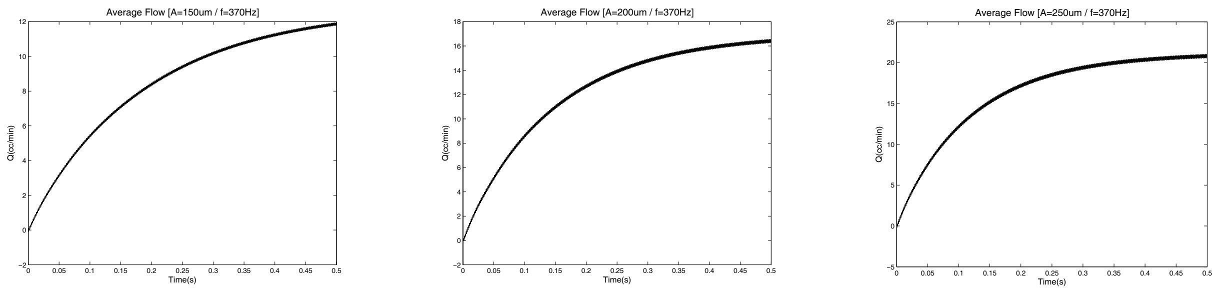
where: L_{inlet} is the length of the inlet section; $L_{actuator}$, the length of the actuator; A, the amplitude of oscillation; f, the frequency of oscillation; h, the height of the outlet section; L_{outlet} , the length of the outlet area (enough for the flow development).

The mesh used for the numerical simulation is represented in Fig. 4(b), which contains around 3100 elements. The mesh density was increased in the region near to the piezoelectric actuator. The parameters used for the simulation were: L_{inlet} = 1mm; $L_{actuator}$ = 39mm; f = 370Hz; h = 4mm; L_{outlet} = 15mm. Various values were considered for the A parameter (displacement amplitude).

The displacement pattern of the actuator was derived from Açikalin; Raman; Garimella (2003). Regarding to the boundary conditions the pressure imposed to outlet and inlet sections is also mentioned. In this case, it was imposed a null differential pressure between the pump inlet and outlet. A situation of the pump inserted in a closed loop system and also the present setup in the experiments carried out are modeled under these conditions.

As it was not possible to obtain a value for the maximum amplitude of oscillation on the actuator, the chosen values for the simulations were: 250µm, 200µm, 150µm. In the first set of simulations it was considered a total time of simulation of 0.1s, corresponding to 37 cycles of oscillation. It was observed that for this time was not enough to ensure a stabilization of the average flow.

Due to the flow across the outlet section has not yet converged to an average value, another set of simulations were conducted considering a total time of 0.5s (a total of 185 oscillation cycles), in which the convergence to an average value can be seen, as it is shown in Fig. 5. At this time, according to the simulation results, the pump has reached a stationary regime, in which the flow generated is constant with time.

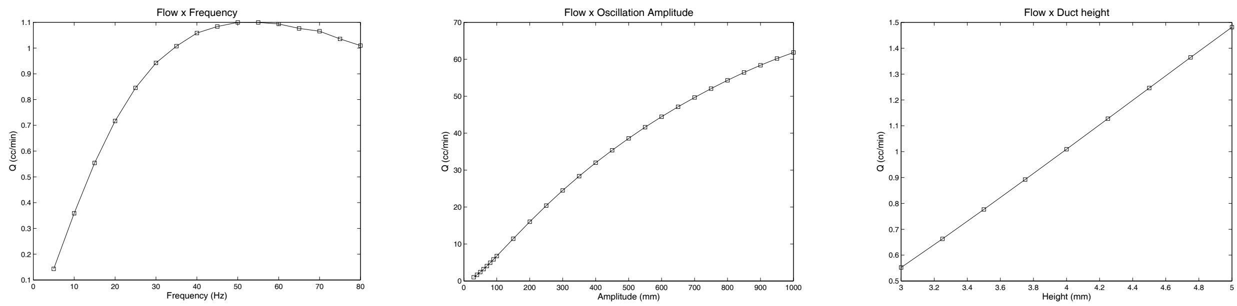


a) b) c)

Figure 5. Flow across the outlet section for 0.5s with 150µm (a); 200µm (b); 250µm (c)

The simulations have given an average flow of 12.0cc/min, 16.0cc/min and 20.8cc/min for amplitudes (peak-to-peak) of 150µm, 200µm and 250µm respectively. As it can be noticed, the average flow has reached an almost stable value in Fig. 5(b). and Fig. 5(c). In the case of the Fig. 5(a), although it still seems to be in a transient regime, the steady flow is expected not to change significantly.

At the same time, a preliminary sensitivity analysis and optimization were carried out. As it started before the results mentioned above were achieved, there are differences between the parameters used in the simulation (the main objective at this time was a verification of workability within the ANSYS® and Altair Hyperstudy softwares). The basic setup considered at this step was a resonant frequency of 80Hz with the actuator modeled as a rigid articulated body, the initial oscillation amplitude considered was 30µm (which resulted in a average flow of 1.01cc/min). In addition to this, the mesh had fewer elements for a matter of simplicity and computational time. The results are shown below:



a) b) c)

Figure 6. Sensitivity analysis for frequency (a), oscillation amplitude (b) and height of the duct (c)

Figure 6(a) shows the sensitivity analysis for the frequency. The other parameters remained the same as those in the basic setup. The frequency has shown an optimum value around 50Hz (1.1 cc/min), however with a small decrease when compared with the basic setup. Figure 6(b) shows the behavior of flow values when the amplitude of oscillation is changed, it was considered a starting point of 30µm going up to 1000µm, with an increasing flow as the amplitude increases (with a maximum of 61.8 cc/min). Finally, the height of the duct was changed and a linear behavior of the flow was observed Fig. 6(c), being proportional to the increase in the height (a maximum of 1.48cc/min was achieved).

After the sensitivity analysis an optimization process was carried out. The Altair Hyperstudy software was used in this step. It interacts with the ANSYS® software, interpreting its results and making the optimization process feasible. The optimization problem was to maximize the average flow such that box constraints for frequency, amplitude and height of the duct were satisfied (5Hz ≤ f ≤ 100Hz; 30μm ≤ A ≤ 1000μm and 3mm ≤ h ≤ 5mm, respectively). The objective function convergence curve obtained is shown below.

Figure 7 shows the objective function value changing from 1.01cc/min to almost 158.17cc/min, indicating how effective the optimization process is. The optimum parameter values were: f=90Hz, A=1000μm and h=5mm. Within these parameters, it was evaluated how a pump with those characteristics would behave. A flow against pressure graph was drawn [Fig. (8)], showing that the pump would generate flow at a maximum pressure of 250Pa in its outlet section.

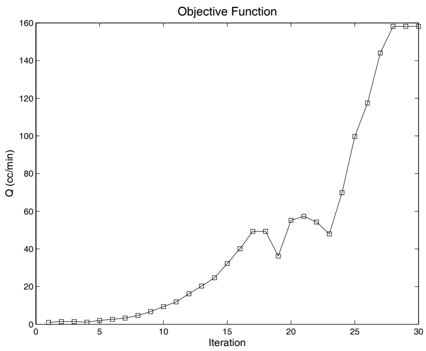


Figure 7. Objective function

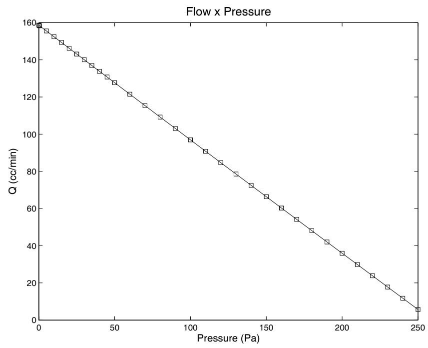
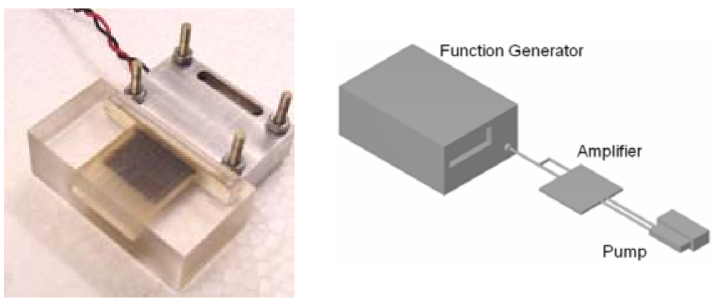


Figure 8. Flow x pressure

4.2. Experimental Results

With the purpose of validating the computational results achieved, an initial experimental prototype was built. The two main parts of the prototype, shown in Fig. 9(a), are: one, built with aluminum, which has a 1mm length clamp area for the actuator, it also has the electric terminals and the cavity beginning until three fourth parts of actuator length; other, built with acrylic, located at the end of the cavity, allowing the flow visualization.



a) b)

Figure 9. Piezoelectric pump prototype (a) and driver circuit of the piezoelectric pump (b)

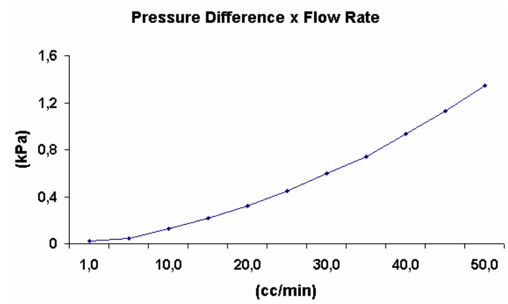


Figure 10. Pressure difference x flow rate

For the experimental tests of the prototype, the present equipments are used: AGILENT 33120A Function Generator, Harvard Apparatus PHD 4400 Hpsi Syringe Pump, Hewlett Packard 4194A Impedance/Gain-Phase Analyzer, glue, bequer, water, potassium permanganate. The driver circuit of the pump was shown in Fig. 9(b).

The first test consisted in determining the load loss of the prototype structure. With a syringe pump, some flow rate values were induced thought the prototype. A pressure transducer was placed between the syringe pump and the prototype. After the test, it was possible to plot the pressure variation of the prototype structure against induced flow, as can be seen in Fig. 10. This kind of test will help in the comparison of different prototypes during this research project in terms of load loss, aiming at a power input reduction.

The next test performed was the flow rate evaluation of the piezoelectric pump. Firstly, the Impedance x Frequency curve of the prototype was taken with the purpose of defining the resonant frequency, where the actuator has maximum amplitude, as it can be seen in Fig. 14(a). After this, the methodology used consisted in connecting a glass tub, with a known length and diameter, to the entry of the prototype and injecting a red color pigment (potassium permanganate).

After turning the pump on, the pigment crosses the pump and is ejected out of the prototype. The experimental test setup is shown in Fig. 11 and Fig. 12.

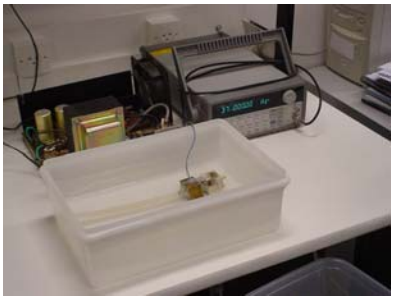


Figure 11. Experimental test setup

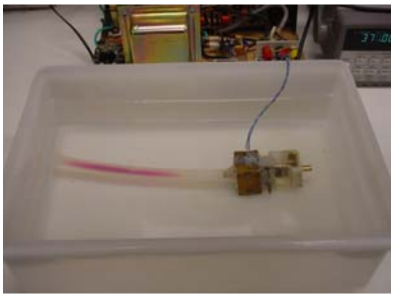


Figure 12. Red color pigment initial position

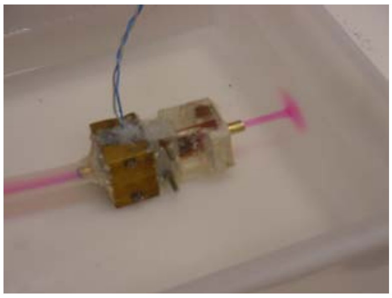
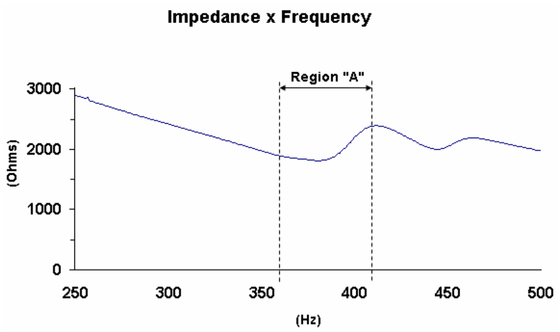
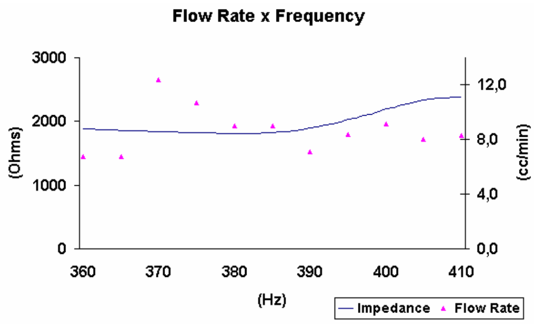


Figure 13. Detail of the flow generated by the pump

During this moment, the velocity of the pigment was taken. The flow was found to be laminar, as it is shown in Fig. 13, due to its Reynolds number (Re = 51,51), so that the average velocity was calculated as a half of the maximum velocity. With this data, it was possible to plot the graph of the piezoelectric pump flow rate against the frequency used, as in Fig. 14(b).



a)



b)

Figure 14. Variation of prototype impedance under the water against frequency (a) and region "A" of the figure. Variation of flow rate against frequency (b)

As noticed, the pump flow rate have a maximum of 12.4 cc/min at 370Hz and decreases both for higher and lower frequencies until become zero far from this band. Then the pump works in a frequency band close to the resonance of the system under the water, as it can be seen in Fig. 14(a).

5. Results Comparison and Discussion

In this section, a comparison between experimental and computational results is carried out.

As mentioned above, the pump has achieved a flow rate of 12.4cc/min at a frequency of 370Hz. As the maximum amplitude of displacement could not be experimentally evaluated yet, the values of 250µm, 200µm, 150µm were considered for the simulations. It is essential to mention that those values were obtained by observing a displacement of 1mm of the actuator in the air, and considering the attenuation caused by the water, the values above were estimated. Flow rates of 20.8cc/min, 16.0cc/min and 12.0cc/min were obtained respectively. Those values shows that computational simulations are ought to produce reliable results for the design of the pump once they are contained in the interval from ~10cc/min to ~20cc/min, in which the experimental result was measured as well.

It cannot be stated with certainty that the maximum displacement of the actuator is 150µm due to the flow rate variability. However, there is a high expectation that the maximum displacement will be close to this.

6. Conclusions and Future Work

Up to this point in the project, results have shown great agreement, showing the validity of the computational models used to simulate this pump and also the importance of a verification of computational results through comparisons with experimental results.

Although the sensitivity analysis and optimization were made with different parameters rather than the ones from the prototypes, they have shown their importance, being capable of increasing drastically the pump performance.

A better investigation around the maximum displacement of the actuator is to be done to make a better evaluation of the computational techniques and its results. A computational load-loss analysis is also to be made to refine the computational models.

The future work for this project will also involve a sensitivity analysis and optimization considering the prototype parameters.

New prototypes will also be built, with the help of computational models to predict the system behavior. An analysis, modeling and construction of new piezoelectric actuator is also aimed for this project. In addition, some values of frequency will be chosen for a study of the pump performance sensitivity relation to the amplitude of the input signal.

Characterization both through experimental and computational techniques will also be carried out.

7. Acknowledgements

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