STUDY OF NOVEL GEOMETRIES FOR OSCILLATORY BIMORPH ACTUATOR OF A PIEZOELECTRIC FLOW PUMP

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Abstract. *Nowadays, precision flow pumps are instruments widely applied through many Engineering areas, such as cooling of electronic components and Bioengineering applications for fluid pumping through an organism. New principles in precision flow pumps development have been extensively proposed, such as the one based on the use of piezoelectric actuators. A piezoelectric flow pump presents some advantages in relation to other solutions, such as miniaturization potential, and fewer numbers of moving parts, and it also offers better performance with low noise and low power consumption. This work presents the development of novel configurations of piezoelectric flow pumps based on the use of oscillatory bimorph actuators with biomimetic tip geometries that are inspired in fish caudal fin shapes. The flow generation principle, based on vortices generated by oscillation of the piezoelectric actuators, is analogous to the fish swimming tail during its locomotion. This flow pump development consists in computational simulations, manufacturing and experimental characterization steps. The main objective is to analyze the efficiency of the proposed shapes of bimorph piezoelectric actuators in fluid pumping. The experimental methodology and obtained results are presented, as well as, a way of analyzing the physical phenomena and validating these new proposed designs.*

Keywords*: oscillatory pump, piezoelectric actuator, experimental characterization, computational simulation.*

1. INTRODUCTION

Precision flow pumps have been studied over the last decades. It has small size, low power consumption, and it can be applied as an essential component for drugs and chemical reagents dosage systems (Tsai and Sue, 2007), and for pumping systems of biological fluids (Andrade et al., 1996), and for cooling systems of electronic equipment. Traditional cooling systems (using fans) have become inefficient to dissipate the heat generated by the modern chips. In order to solve these technological problems, water cooling systems based on precision flow pumps and small heat exchangers, having higher thermal dissipation capacity, have been proposed by many researchers (Singhal et al., 2004).

Several works use piezoelectric actuators in precision flow pumps since it presents some advantages in relation to other solutions, such as miniaturization potential, lower noise generation, and fewer numbers of moving parts (Kim et al., 2004). Bar-Cohen and Chang (2001) presents an ultrasonic pump which uses stators piezoelectrically actuated to generate a propagating wave that moves the fluid. This kind of flow pump has also been developed by other researches (Smits, 1990; Teymoori and Abbaspour-Sani, 2005; Jang and Kan, 2007). Other example is a diaphragm pump, in which the piezoelectric actuator works as a membrane that forces fluid through a small chamber, having the flow direction controlled by check valves (Meng et al., 2000). Another example of piezoelectric pump has been studied by Kar et al. (1998), which is based on a mechanism similar to a syringe that uses a piezoelectric actuator to control its dosage.

Lima et al. (2009) presents the principle of a novel pump configuration based on placing a rectangular oscillating bimorph piezoelectric actuator in a fluid channel to generate flow. The proposed principle of pumping mimics the phenomenon of swimming fish (Sfakiotakis et al., 1999), through an oscillatory motion generated by a thin plate oscillating inside a fluid environment. This oscillatory behavior yields vortex interaction that result a flow rate due to the action and reaction principle.

Investigation of vibration modes, in what such phenomena occurs, gives motivation for the exploration of new shapes for the bimorph piezoelectric actuator. Thus, the objective of this work is the development of novel configurations of piezoelectric flow pumps, in order to explore the novel pump principle proposed by Lima et al. (2009), aiming to maximize the pump performance. It is based on the use of bimorph actuators with biomimetic tip geometries, which are inspired in fish caudal fin shapes.

In the next sections, the complete cycle of pump development is shown. Initially, section 2 presents the fundamental theory. In section 3, proposed fish caudal shapes are described. Section 4 shows analysis of proposed caudal shapes from computational simulations. Section 5 describes the applied experimental apparatus and results achieved using manufactured prototype pump. Finally, conclusion about obtained results is given in Section 6.

2. FUNDAMENTAL THEORY

The wake generated by fish that swims due to undulatory and/or oscillatory motion of their bodies and caudal fins is a discrete vortex street of alternating signal, as it can be seen in Fig. 1. This vortex street has reversed rotational direction compared to the Karman vortex street, which produces drag force around bodies placed in a free stream (Sfakiotakis et al., 1999), and then, flow generation between the vortices can be observed.

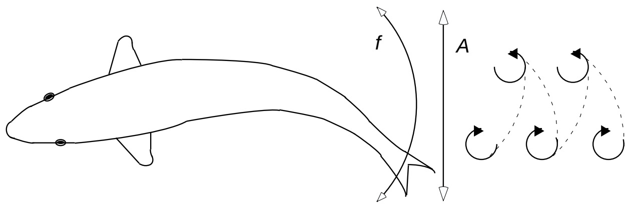


Figure 1. Vortex street wake generated by a fish swimming

Similar vortex street generation is also observed in oscillatory motion of a thin plate inside a fluid environment (Açikalin et al., 2003). In this way, each generated vortex drives the one generated previously in opposite direction to the actuator (thin plate), resulting in a flow rate to the right side due to the action and reaction principle. Lima et al. (2009) explores this working principle by applying it to a novel pump configuration based on oscillating bimorph piezoelectric actuator placed in a fluid channel to generate flow, as illustrated in Fig. 2.

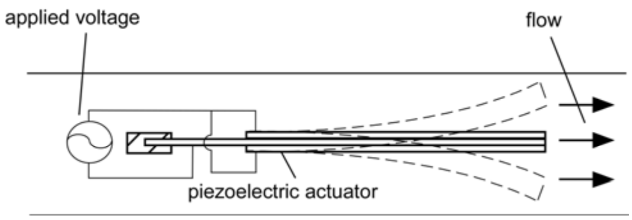


Figure 2. Piezoelectric pump scheme

In this work, the influence of using bimorph piezoelectric actuators with different caudal shapes is investigated. 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 layers. When an electric voltage is applied to the ceramic, the metallic plate is deformed proportionally to the applied voltage, as illustrated in Fig. 2. Combination of a bimorph (PZT/metal/PZT) allows such displacements since a piezoelectric ceramic is expanded the other is compressed, bending the actuator. A bimorph actuator shows relative high displacements (~1 mm), however with very low forces. Operating in resonant frequency its typical response is achieved around 50 μm/V.

3. PROPOSED SHAPES

Different geometries that mimic fish caudal shapes (shown in Fig. 3) are reproduced on thin metallic plates, which are assembled at the free end of the bimorph piezoelectric actuator. These caudal shapes were also studied by Wiguna et al. (2005) to analyze its influence in fish robot propulsion. Vibration modes of each piezoelectric actuator configurations (with attached fish caudal shape plates), are calculated and its effect in vortex generation at pumping flow is investigated.

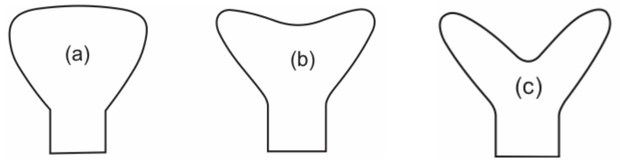


Figure 3. Fish caudal shapes: a) ostraciiform; b) subcarangiform; c) carangiform

The first proposed shape is based on fish caudal ostraciiform shape (Fig. 3a) which has a triangular geometry with small elongation in central region. Other configuration, based on fish caudal subcarangiform shape (Fig. 3b), has a triangular geometry with small concavity in central region. This concavity generates a narrow tip region, which reduces the stiffness of this region, yielding a high amplitude oscillatory tip. Another study is made considering configuration based on fish caudal carangiform shape (Fig. 3c), which has a large concavity in central region. Fish with caudal carangiform shape uses one third of its body for oscillatory propulsion, while the fish with caudal subcarangiform shape uses a large fraction of its body (half up to two thirds) for locomotion (Sfakiotakis et al., 1999).

Computational simulations, using finite element analysis (FEA) software, are carried out for piezoelectric actuators with attached thin metallic plates (fish caudal shapes) presented in this section. After that, experimental prototype characterization is made to investigate flow rate generated from each piezoelectric actuator configuration.

4. COMPUTATIONAL SIMULATIONS

The use of computational models allows the evaluation of a given system behavior reducing the prototyping construction cost. Thus, computational models of the bimorph piezoelectric actuator, considering geometric parameters (L, D, and W) shown in Fig. 4, are simulated through an acoustic analysis. From this analysis, the system resonant frequencies and vibration modes both in air and in liquid environment are identified.

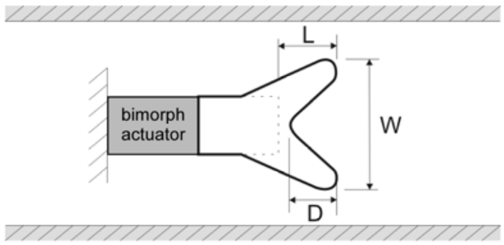


Figure 4. Parametric model for acoustic analysis

In this work, the piezoelectric pump simulation is performed by using the ANSYS software, however any other appropriate FEA tool could also be used. An acoustic model of the pump water channel is created by using FLUID30 element (Ansys, 2003) to simulate fluid-structure interaction. Inside the channel, the bimorph piezoelectric actuator is modeled by using SOLID98 element that allows performing tridimensional simulations of structural materials, such as the metallic plate and piezoelectric material.

Figure 5 shows a section view of the FE mesh (with tetrahedral elements) used in computational simulations. An intermediate region (red layer in Fig. 5) between solid region (piezoelectric actuator and duct walls) and fluid medium (water) is needed to provide fluid-structure phenomena.

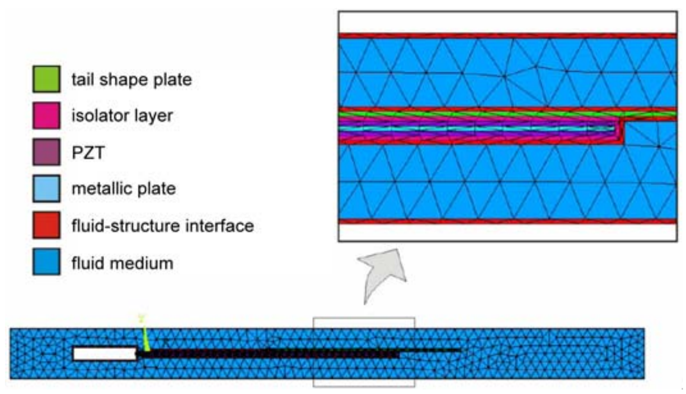


Figure 5. Section view of FE mesh used in simulations

The fluid medium adopted in this work is water, and the boundary conditions of pump channel model used in the acoustic analysis consists of applied voltage values for electrode regions (equal to 30V at PZT element and 0V at metallic plate element), and null displacement values for region near the piezoelectric actuator clamp.

Convergence analysis is performed to determine the influence of the mesh discretization in simulations. According to computational simulations, the FE mesh composed by 200,000 elements (approximately) is chosen since frequency and amplitude convergence is found for this discretization. Moreover, it is noticed that for larger refined mesh the computational cost is very high.

The vibration modes and the frequency spectrum are obtained for the same geometric parametric model shown in Fig. 4, using the following adopted parameters: W=40 mm; L=20 mm; and D=10 mm. Figure 6 presents the third vibration modes of the system composed by piezoelectric actuator and thin plate. In this work, the third vibration mode is chosen for all computational models since it is a variation of the actuator second mode, which is characterized by a peak formation in the middle of the actuator. From Fig. 6, it is noticed that thin plate tip behavior presents higher displacements, whose probable effect is to provide higher fluid flow generation.

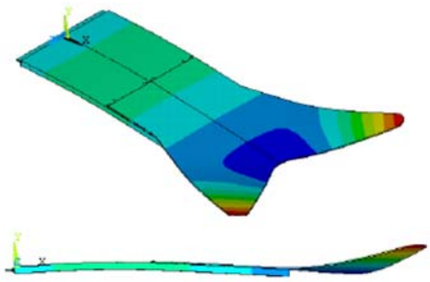


Figure 6. Third vibration mode

Here, obtained frequency values are related to the piezoelectric actuator impedance values near its resonant frequency. The experiments are conducted in the resonant frequency because the maximum electromechanical conversion of material occurs in this frequency, which results in large displacements.

A sensitivity analysis is also performed. Essentially, it consists of changing parameter values (W, L, and D) of the parametric model shown in Fig. 4 to verify the influence of each one in the obtained results. Several different possible combinations of these parameters are also tried out in order to find better performance of the system composed by piezoelectric actuator and fish caudal shape plate. The model used in convergence analysis (W=40, L=20, D=10) is chosen as reference model for comparison, using results obtained in the sensitivity analysis. As selection criteria, the chosen combination should give high amplitude together with high frequencies for maximizing piezoelectric pump performance. Thus, the best simulation results are obtained for parameter combinations shown in Tab. 1.

Table 1. Computational results obtained in acoustic simulations

W (mm)	L (mm)	D (mm)	F (Hz)	Displacement (mm)
40	20	10	**369.0**	**1.412**
30	20	10	**412.0**	**1.361**
30	15	10	**529.0**	**1.532**
40	15	10	**446.5**	**1.504**
40	20	0.5	**358.0**	**1.377**
40	20	5	**358.0**	**1.590**

The displacement of the piezoelectric actuator found in this harmonic analysis could be prescribed as boundary condition in a fluid flow simulation to reproduce the behavior of the flow pump. However, a fluidic analysis requires high computational time making unfeasible to drive simulations of high number of models with distinct parameter combinations. Due to this, experimental approach is adopted to verify flow rate levels of the best models studied in acoustic analysis (W, L, D combinations shown in Tab. 1).

5. EXPERIMENTAL RESULTS

5.1. Experimental Apparatus

The experimental apparatus utilized in this work is designed to allow making changes in the pump channel geometry quickly. Figure 7 illustrates this apparatus.

The experimental characterization consists of obtaining electrical impedance curves for each piezoelectric actuator configuration and the respective flow rate values. The electrical impedance curves for a frequency range are obtained by using a HEWLETT PACKARD 4194A impedance analyzer. The frequency range adopted varies from 100Hz (minimum frequency of the instrument) to 1200Hz.

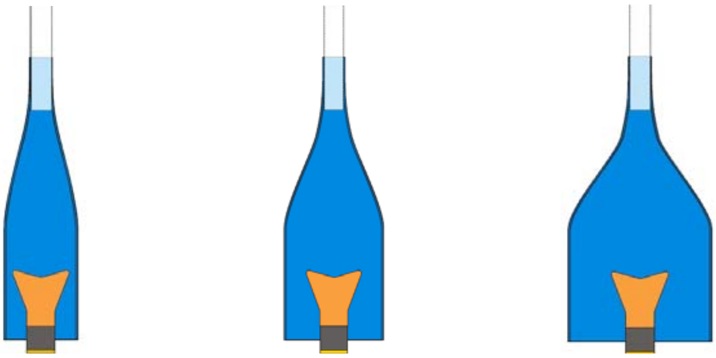
The pump flow rate measurement is made by measuring the maximum flow velocity inside a cylindrical tube, made of acrylic material. This tube has 12.7 mm diameter and 75 mm length, and it is placed inside a channel where the water flows. By measuring the time that the liquid (water) takes to cross the known tube length, the flow rate can be calculated (Fox and McDonald, 1998). Thus, based on the continuity principle, it is concluded that flow rate generated by the flow pump inside the channel is the same as the one calculated inside the tube. To facilitate the time measurement a red pigment is used in the water, allowing to visualize the fluid flow inside the system.

Figure 7. Experimental apparatus

5.2. Results

Prototype of each piezoelectric actuator configurations (with attached fish caudal shape plate), which respective models provide the best results in computational simulations (see W, L, D combinations shown in Tab. 1), are constructed and their corresponding electrical impedance curves are determined in air and water. Through these obtained electrical impedance curves it is possible to determine the resonant frequencies for each prototype and, consequently, probable excitation frequencies that produce higher flow rate. The values obtained in this electrical impedance analysis provide data input for the flow rate experimental tests shown in this section.

Figure 8 illustrates apparatus configurations considered for experimental flow rate measurement. Three different channel width values (60, 80, and 100 mm) are tested. In this case, the influence of these dimension parameters in flow rate measurement is verified.



(a) (b) (c)

Figure 8. Tested pump channels: (a) width = 60 mm; (b) width = 80 mm; (c) width = 100 mm

The flow rate measurement is carried out for all constructed piezoelectric actuator configurations, however the best results is obtained for prototype with parameters equal to W=40 mm, L=20 mm, and D=0.5 mm. The flow rate values obtained considering the tested pump channels (see Fig. 8) are 114 ml/min, 95 ml/min, and 85 ml/min, respectively (60, 80, and 100 mm of channel width). The obtained results correspond to frequencies in which the pump presented the best performance in terms of flow rate.

For comparison, the adopted reference flow rate value is 81.4 ml/min (at 414 Hz). This reference value is achieved by using a rectangular piezoelectric actuator (40 mm length, 20 mm width, and 0.6 mm thickness) in channel of Fig. 8a, and without attached caudal shape plate.

6. CONCLUSION

Computational simulations are performed to determine resonant frequencies and respective vibration modes of the novel configurations of bimorph piezoelectric actuator. Through this development, it is possible to find parameters that have considerably influence in flow pump performance. According to obtained results, the channel dimensions have influence in generated flow rate values. It is concluded that using of biomimetic tip geometries on bimorph piezoelectric actuators for applications in fluid pumping provides good effects in the performance of oscillatory piezoelectric flow pumps. In some cases, the application of fish caudal shapes at free end of the piezoelectric actuator gives higher flow rate, achieving an improvement of 40% in terms of flow rate, in relation to the bimorph piezoelectric actuator with traditional rectangular shape.

As suggestion for future work, a more complete analysis of the influence of channel profile in the performance of oscillatory piezoelectric flow pumps will be conducted through fluidic simulations, contributing to improve the knowledge about the involved phenomena. Finally, a study about this system miniaturization to obtain more compact apparatus is also suggested.

7. ACKNOWLEDGEMENTS

The authors would like to acknowledge FAPESP, CNPq and CAPES for the financial support provided for this project through fellowships and a PIPE project (2004/14675-0).

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