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Piezoelectric Pump Used in Bionic Underwater Propulsion Unit

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Abstract

A new piezoelectric pump can pump liquid either forward or backward and adjust the flow rate. Thus an object can be driven forward or backward at different speeds. The driver of the pump, a circular piezoelectric plate, is modelled by Finite Element Method (FEM) in ANSYS and its performance is simulated and analyzed. The pump gives the best performance when the driving signals of the inlet and outlet valves have a bigger duty cycle and the plate has a higher voltage applied.

Keywords: underwater propulsor, piezoelectric pump, actively controlled valve, magnetic coil

1 Introduction

The cuttlefish moves by generating a water jet. By changing the direction of the jet, the cuttlefish can go forward and backward freely. Similarly a jet propulsor is designed and used in jet plane and rocket. The earliest water jet propulsor was created by Toogood and Hays in 1661. From then on, in the UK, France and the USA, many scientists tried to design better water jet propulsors[1,2]. Until the 1980 s, this kind of propulsor progressed so well that it could generate power of tens of thousands of watts, but their prime movers and mechanical structures were huge. For a micro propulsor with smaller output power, especially used in the bionic area, a conventional water jet propulsor is not an obvious starting point.

For this reason, a new piezoelectric pump which can be used by a bionic underwater propulsor is developed in this paper. It drives the object by pumping the liquid from the front to the rear. A piezoelectric pump is of compact and simple structure, generates no magnetic interference, and is light, cheap and easy to control[3–5]. Actually, the piezoelectric pump has been widely used in the medical, chemical and mechanical fields for a very long time[6–8]. It can be categorized by the type of valves. Commonly a piezoelectric pump with passive silicon or metal valve is used[9,10]. But this kind of pump is able to pump the liquid only in one direction. A piezoelectric pump with active valves can, by shifting the phase of the power signal, transport the liquid either forward or backward, which means that this pump can be used to drive an underwater machine going forward or backward and even steering. Therefore, the piezoelectric pump with active valve is selected as the prime mover of the underwater propulsor.

2 Materials and methods

2.1 Mechanical structure

The mechanical structure of the new propulsor is shown in Fig. 1. It is composed of three main parts, the piezoelectric pump, the inlet pipe and the outlet pipe. The piezoelectric pump includes upper and lower covers, pump chamber, pump body, inlet and outlet valves, magnetic coils, springs and two piezoelectric circular plates. The pump is driven by the piezoelectric circular plates. The inlet and outlet valves are opened by magnetic coils and closed by springs. Several O-rings are also used to seal the pump.

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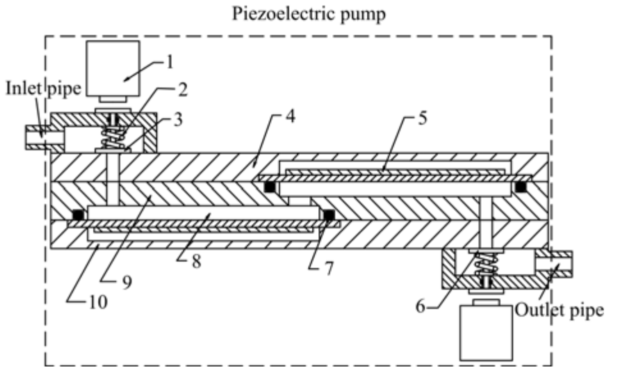


1 Magnetic coil, 2 Spring, 3 Inlet valve, 4 Upper cover, 5 Piezoelectric actuator, 6 Outlet valve, 7 O-ring, 8 Pump chamber, 9 Pump body, 10 Lower cover.

Fig. 1 Structure of the designed piezoelectric pump.

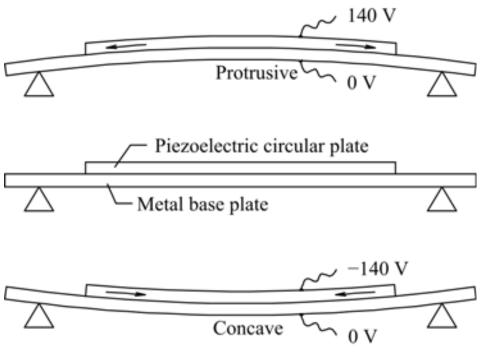


Fig. 2 Different state of the piezoelectric circular plate.

The piezoelectric plate is a special kind of actuator comprising a piezoelectric disk and metal base plate as shown in Fig. 2. These two parts are glued together. When a voltage is applied to the disk, it expands or contracts which causes the metal base plate to bulge or become concave respectively. This deformation of the plate generates the intake and exhaust actions of the pump. The properties of the piezoelectric circular plate used in this paper are listed in Table 1 and Table 2.

Table 1 Dimensions of piezoelectric circular plate

	Diameter (mm)	Thickness (mm)	Material
Piezoelectric disk	23	0.2	PZT
Metal base plate	35	0.3	Be-bronze

Table 2 Properties of the materials

Material	Density (kg·m^{-3})	Elastic modulus (GPa)	Poisson's ratio
PZT	7600	63	0.32
Be-bronze	8920	118	0.35

The piezoelectric and stiffness matrices of PZT used in this paper are:

$$[e]=\begin{bmatrix} 0 & 0 & -4.1 \\ 0 & 0 & -4.1 \\ 0 & 0 & 14.1 \\ 0 & 0 & 0 \\ 0 & 10.5 & 0 \\ 10.5 & 0 & 0 \end{bmatrix} \tag{1}$$

$$[c]=10^{10}\times\begin{bmatrix} 13.2 & 7.1 & 7.3 & 0 & 0 & 0 \\ 7.1 & 13.2 & 7.3 & 0 & 0 & 0 \\ 7.3 & 7.3 & 11.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2.6 \end{bmatrix} \tag{2}$$

2.2 Working principles

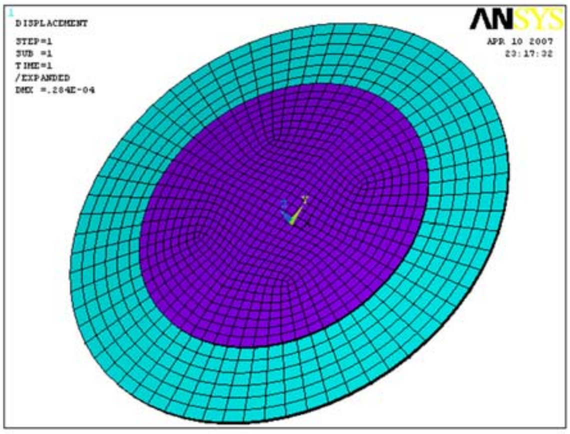
When the pump starts working, the control signal is applied first on the inlet magnetic coil. Then the inlet valve is opened by the magnetic force. After that, under the positive applied voltage, two piezoelectric circular plates at the same time deform outward from the chamber. Thus the volume of the chamber increases, the pressure inside the chamber decreases, and water will be sucked into the chamber by the pressure difference. At the completion of intake, the inlet valve is closed and the outlet valve is opened. Consecutively, with the negative applied voltage, the piezoelectric circular plates deform inwards which decreases the volume of chamber and increases the pressure inside the chamber, thus the water is pushed out of the chamber. Finally, the outlet valve is closed. Repeating the above steps, the water is transported continuously from the inlet to the outlet.

2.3 Performance of the piezoelectric circular plate

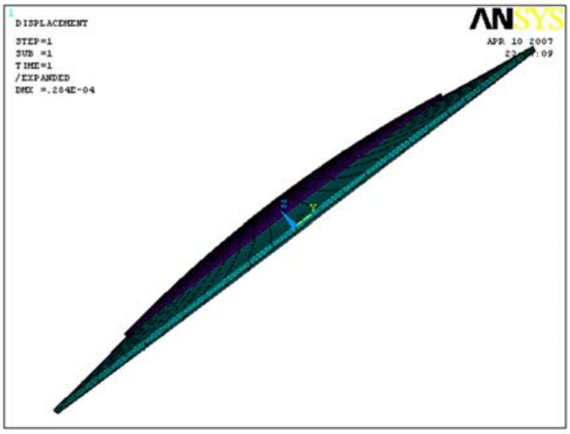
We used FEM software ANSYS to analyse the performance of the piezoelectric circular plate. The displacement of the plate in the normal direction was simulated. The change of volume of the pump chamber can be calculated by the variation of this displacement and consequently the flow rate of the pump can be calculated. To validate the results of simulation, the displacement was measured by devices as well.

The finite element model of the plate is shown in

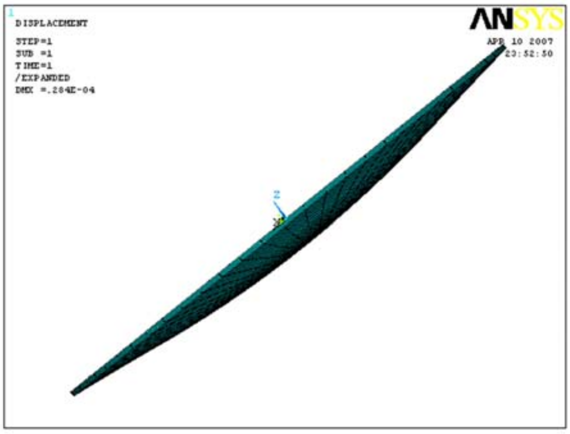
Fig. 3a. According to the working conditions and installation of the plate, zero displacement of the edge of metal plate is assumed as the boundary condition and the voltage of ±140 V applied on the disk is adopted as the load. Figs. 3b and 3c show the simulated deformations of the piezoelectric plate under ±140 V.



(a) FEM Model



(b) Deformation under 140V



(c) Deformation under −140V

Fig. 3 FEM simulation of piezoelectric circular plate.

The simulation calculated the radial deflection of the plat (Fig. 4). The maximum displacement of 28 μm occurs in the centre of the plate. The line labelled ANSYS describes the deformation of the plate from the boundary to the centre along the radius. The deformation of the plate is similar to a parabola which has the same vertex and ends as ANSYS. The maximum absolute displacement error is only 2.8 μm and the relative error is only 0.1% between the ANSYS result and the parabola analogue which means that the deformation of the plate can be represented approximately by a parabola.

Using laser measurement devices, the displacement of the centre of the disk was measured as 28.8 μm under 140 V. Compared with 28 μm from the ANSYS model, the result of the simulation is quite close to the real results which supports the accuracy of the FEM model built in ANSYS.

Based on the formula for a parabola, the deformation of the plate can be expressed as:

$$w(r) = -0.0914\times10^{-4}\times r^{2} + 0.028, \tag{3}$$

where w (mm) is the displacement in the normal direction, r (mm) is the radial variable of the piezoelectric circular plate.

Therefore the theoretical maximum change of volume of the chamber, V (μL), can be calculated by

$$V = \int_{0}^{2\pi}\int_{0}^{a} w(r) r \mathrm{d}\theta \mathrm{d}r = 2\pi\int_{0}^{a} w(r) r \mathrm{d}r\ , \tag{4}$$

in which a is the radius of the plate.

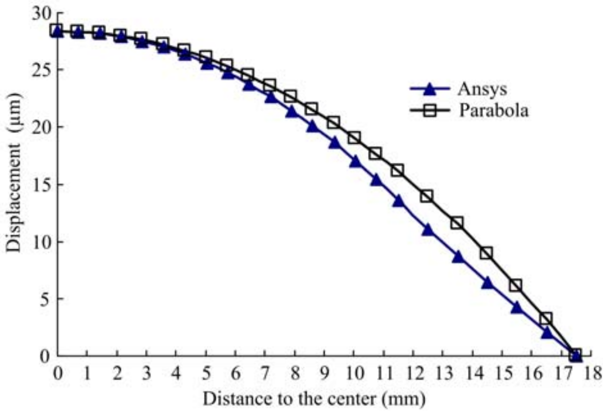


Fig. 4 Results of deformation of piezoelectric circular plate by simulation.

The theoretical maximum flow rate of the pump, Q ($\mu\text{L}\cdot\text{min}^{-1}$), can be calculated by:

$$Q = 2 \times V \times f \times 60 , \tag{5}$$

where f is the frequency at which the pump works.

3 Results and discussion

In addition to the analysis of the performance of piezoelectric circular plate, the frequency response of the magnetic coil was also tested because it does not work well at high frequency. The maximum frequency, under which the magnetic coil can work is 30 Hz, measured under test conditions, so the maximum working frequency of the piezoelectric pump is also 30 Hz.

The piezoelectric pump was tested to explore the effects of the properties of the driving signal such as duty cycle, phase, and applied voltage on the performance of the piezoelectric circular plate and the pump as a whole.

Compared with sinusoidal and triangular waves, a square wave reaches its peak value most quickly. Therefore a square wave was selected as the driving signal. Because the pump is driven directly by the piezoelectric plate, the pump will get the maximum variation of volume fastest if the plate gets its maximum deformation as quick as possible. As a result the pump will have maximum flow rate. The maximum voltages which can be applied to the piezoelectric disk and the magnetic coils are 140 V and 12 V respectively. So to make the pump perform the best these two values are used.

3.1 Characteristics of flow rate against duty cycle and phase

The duty cycle and phase of the driving signal play important roles in the duration of opening and closing of the valve. A bigger duty cycle means the valve will be opened or closed for longer and a small phase means that the valve will be opened or closed earlier with respect to the action of the piezoelectric circular plate.

If the inlet valve opens or the exhaust valve closes much later than the intake action of the pump, intake will be affected, consequently less liquid will be sucked into the pump chamber. On the other hand, if the outlet valve opens or the intake valve closes much later, exhaust will be influenced which leads to less liquid being pumped out. In order to make the plate perform perfectly and efficiently, a duty cycle of 50% is adopted for the driving signal. This means that the pump will use half a cycle of driving signal to take in the liquid and the other half to pump it out.

In addition, to keep the intake and exhaust functions of the pump symmetrical, the duty cycle and phase of the driving signal of the magnetic coils should correspond as shown in Fig. 5. The values used are shown in Table 3. A working frequency of 30 Hz was used in this test.

Table 3 Duty cycle and phase used in the test

Duty cycle (%)	Phase (degree)		
	Inlet valve	Outlet valve	Piezoelectric actuator
30	35	217	0
40	18	198	0
50	0	180	0

From Fig. 5, if the phases of intake and exhaust valve exchange, the intake valve will be the exhaust valve and *vice versa*, which means liquid can be pumped either forward or backward under the active control of the valves. Fig. 6 shows the experimental results of the relationship between the duty cycle and the forward and backward flow rates respectively. When pumping forward, prolonging the duty cycle, the flow rate increases linearly and reaches a maximum of 164 $\text{mL}\cdot\text{min}^{-1}$ with 50% duty cycle, and when pumping backward there is no significant difference from the forward flow rate.

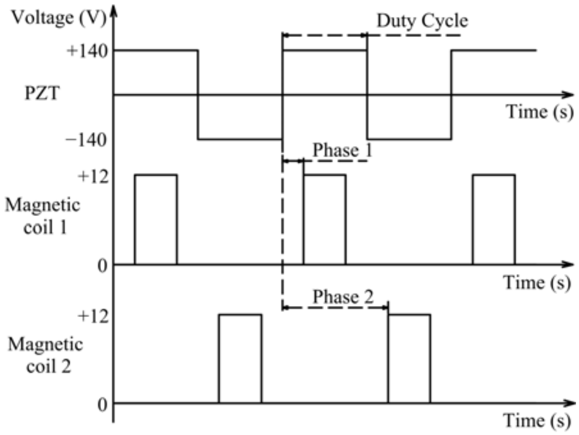


Fig. 5 Driving signals of the pump

The reason is that with a bigger duty cycle the liquid has more time to be sucked into, and pumped out of, the pump chamber. Consequently the flow rate increases. Hence, with a driving signal of 50% duty cycle and differential phase of 180 degrees, the pump gets the maximum flow rate.

3.2 Characteristics of flow rate against applied voltage

The applied voltage on the piezoelectric plate is another important factor which influences the performance of the pump, so it was tested under applied voltages of 80 V, 100 V, 120 V, and 140 V. In this test, the working frequency was 30 Hz, and the duty cycle and phase were 50% and 180 degrees respectively.

The flow rate increases with the applied voltage (Fig. 7). When pumping forward, the flow rate increases from 112 mL·min^{-1} to 164 mL·min^{-1} as the applied voltage changes from 80 V to 140 V. This is because when the applied voltage is high, the piezoelectric plate has a larger deformation which generates a greater change in the volume of the pump chamber per unit time; as a result the flow rate increases. When pumping backward, the flow rate is little different from pumping forward, and varies only from 105 mL·min^{-1} to 154 mL·min^{-1}. The possible reasons for the difference of flow rate between the two directions may be that the seal or the mechanical structures of inlet and outlet valves are not exactly the same.

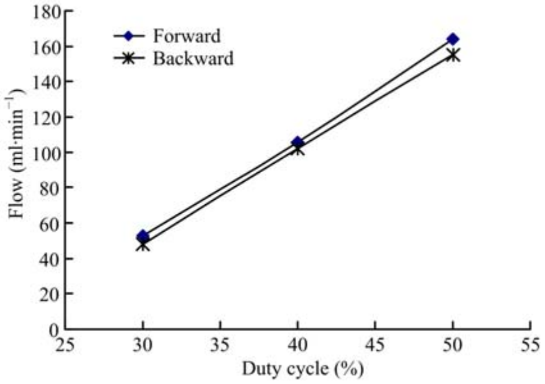


Fig. 6 Characteristic of flow rate against duty cycle.

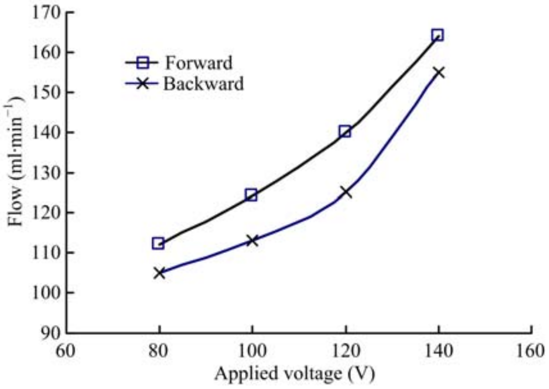


Fig. 7 Characteristic of flow rate against applied voltage.

3.3 Application of piezoelectric pump to bionic underwater propulsor

Based on the above explanation and description, we have shown that the piezoelectric pump can pump liquid forward and backward, and control the flow rate by adjusting the duty cycle of the driving signal of the inlet and outlet valves or the applied voltage on the piezoelectric actuator. Additionally, it has the advantages of small dimensions and simple power supply. All of these make the piezoelectric pump possibly useful in a bionic underwater propulsor.

By pumping liquid forward or backward, the piezoelectric pump is able to drive the object forward or backward. By controlling the flow rate, the speed of the object can also be controlled. Small dimensions make it easy to be embedded into a small underwater robot.

4 Conclusions

A new piezoelectric pump which can be used as a bionic underwater propulsor is designed. By simply shifting the duty cycle and phase of the driving signal of the inlet and outlet valves, the pump is able to pump the liquid in two directions with different flow rates. By adjusting the applied voltage on the piezoelectric actuator the flow rate of the pump can be controlled. If this pump is used as the bionic underwater propulsor, the object can go forward and backward at different speeds.

Although the piezoelectric pump is not as good as current underwater propulsors, it provides a new concept. Apparently, further research on a piezoelectric pump of underwater propulsor is necessary.

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References

[1] Roy S M. The evolution of the modern water jet marine propulsion unit. *International Conference on Water Jet Propulsion I*, London, UK, 1994.

[2] Liu C J, Wang Y S, Ding J M, Sun C L. The evolution of the modern water jet marine propulsion unit. *Ship Science and Technology*, 2006, **28**, 8–12, in Chinese.

[3] Kan J W, Yang Z G, Cheng G M. Research on piezoelectric pump and its development. *Optics and Precision Engineering*, 2002, **10**, 619–625, in Chinese.

[4] Jiao X W, Huang W Q, Zhao C S. The Piezoelectric Pump Technology and its Application. *Micromotors*, 2005, **38**, 66-69, in Chinese.

[5] Feng G H, Kim E S. Micropump based on PZT unimorph and one-way parylene valves. *Journal of micromechanics and microengineering*, 2004, **14**, 429-435.

[6] Kojima Y, Okusawa T, Tsubouchi K, Hamano N, Takagi Y. Fundamental investigation of a piezoelectric pump for a trace liquid feed. *JSME International Journal C: Mechanical Systems*, 1995, **38**, 531–537.

[7] Cao L, Mantell S, Polla D. Design and simulation of an implantable medical drug delivery system using microelectromechanical systems technology. *Sensors and Actuators A: Physical*, 2001, **94**, 117–125.

[8] Teymoori Mir Majid, Abbaspour-Sani Ebrahim. Design and simulation of a novel electrostatic peristaltic micromachined pump for drug delivery applications. *Sensors and Actuators A: Physical*, 2005, **117**, 222–229.

[9] Mauck L D, Lynch C S. Piezoelectric hydraulic pump development. *Journal of Intelligent Material Systems and Structures*, 2000, **11**, 758–764.

[10] Li B, Chen Q F, Lee D G, Woolman J, Carman Greg P. Development of large flow rate, robust, passive micro check valves for compact piezoelectrically actuated pumps. *Sensors and Actuators A: Physical*, 2005, **117**, 325–330.