Design and Prototyping of a Novel Type Piezoelectric Micro-pump

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Using the extensional vibration mode of PZT ring, a piezopump is successfully made. The PZT ring is polarized with thickness direction. The traveling extensional wave along the circumference of the ring is obtained by dividing two standing waves which are temporally and spatially phase shifted by 90 degrees from each other. The proposed piezopump is consisted of coaxial cylindrical shells that are bonded piezoelectric ceramic ring. The pump takes an unobtrusive operation into the simple displacing mechanism using peristaltic traveling waves without the physical moving parts. The finite elements analysis on the proposed pump model is carried out to verify its operation principle and design by the commercial FEM software. Components of piezopump were made, assembled, and tested to validate the concepts of the proposed pump and confirm the simulation results. The performance of the proposed piezopump is about 580 μl/min in flow rate with the highest pressure level of 0.85 kPa, when the driving voltage is 150 V_p, 57 kHz.

Keywords : Piezoelectric pump, Rotary piezoelectric motor, Peristaltic traveling wave, Extensional traveling wave of ring, Co-axial cylindrical shell pump

1. INTRODUCTION

A piezoelectric pump has been researched for some various applications[1,2]. Piezopump systems typically operate by pushing fluid through check valves to produce positive fluid flow. The function of the piezopump is to convert the very small displacements of the piezoelectric actuator into useful works. The major operation of pumps is based on the reciprocating motion. Most of pumps consist of a chamber to drive an actuator, and the check valves to take an on/off role of input and output. But these valves have some problems such as abrasion, fatigue and clogging condition[3,4].

In order to eliminate the critical problems, there are a number of considerations for the valveless pumps. One of the valveless pumps is the peristaltic pump which uses three pumping chambers with diaphragms as actuators in series. This peristaltic pump applies to both fast and slow actuation mechanisms such that it can used for piezoelectric, pneumatic, thermo pneumatic and other driving effects[5,6]. However, overheating in thermo pneumatic actuators can result in the deterioration of biomaterials.

In this paper, we propose a simple and novel design of piezopump driven peristaltically by a piezoelectric actuator. In this piezopump, a volume displacing mechanism using extensional traveling waves of ring, which acts peristaltically and allows the elimination of the need for valves or physically moving parts, induces the pumping effect. A numerical simulation of the piezopump will be used to verify the operation principle.

A modal and harmonic analysis of the proposed piezopump model will be performed for its design. The design allows directly determining the modes of piezoelectric pump that are associated with the several resonance frequencies. The simulation is affected essentially from piezoelectric design parameters and pump geometry. In order to optimize the pump efficiency for choosing the pump volume, the model is modified to evaluate the harmonic analysis.

2. PRINCIPLE OF OPERATION

In the past two decades, various types of piezoelectric actuators such as rotary motors, inchworms, linear motors, and other drive mechanism[7,8]. These motors offer several advantages in the area of power efficiency, torque density, compact size, high torque at low speed, large holding torque, and so on. This motor technology provides the basis for a piezoelectric pumping mechanism that can be used to transfer fluids between media. To assist in understanding the pumping mechanism, the piezoelectric motor technology is reviewed briefly. In Fig. 1, the operation principle of piezoelectric motor is shown, where the stator, actuated by the piezoelectric ceramics, propels a rotor that is in intimate contact with it. A traveling flexural wave is established over the surface of the elastic stator that propels the rotor pressed onto it using the elliptical particle motion. This operation of piezoelectric motors depends on friction at the interface between the stator and rotor.

Reviewing the operation principle of the piezoelectric motor, it is easy to see the formation of multiple chambers between the crests of the traveling wave. These chambers offer a platform for the transportation of capture fluid in the direction of the wave propagation. The operation principle of piezopump is base on using multiple chambers as shown in Fig. 2.

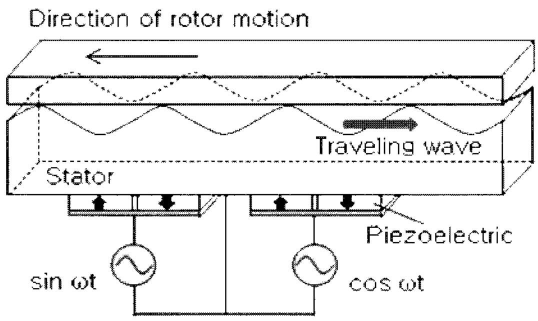


Fig. 1. Principle of operation for piezoelectric motor.

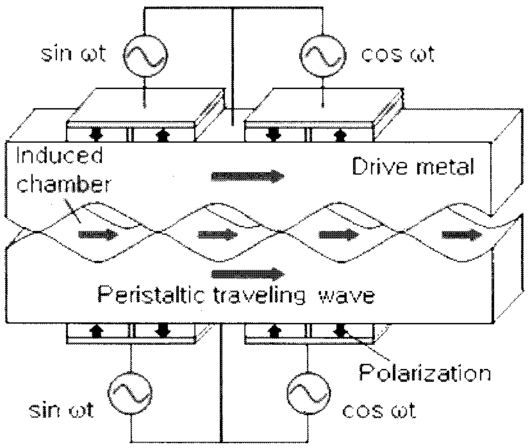


Fig. 2. Principle of peristaltic traveling wave operation for the piezopump.

In a rotary piezoelectric motor which employs vibrations of a ring, there are three vibration modes: 1) flexural vibration in the plane of the ring, 2) flexural vibration at a right angle to the plane of the ring, and 3) extensional vibration. Yoseph Bar-Cohen and Zensheu Chang suggested the first model of peristaltic piezopump using the flexural vibration mode in the plane of the ring[9]. In this paper the peristaltic piezopump using extensional vibration mode of ring is proposed firstly.

K. Lim, et al suggested the piezoelectric rotary motor using traveling wave of screw form as shown in Fig. 3 [10].

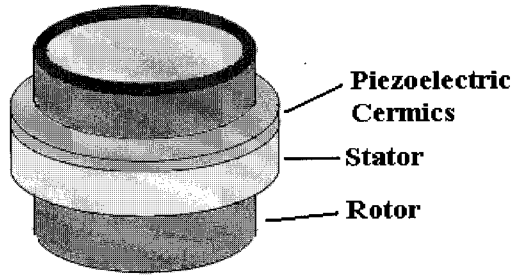


Fig. 3. Piezoelectric motor using traveling wave of screw form.

This motor is operated by using extensional vibration mode of ring. If the stator ring is assumed as shape of cylindrical shell in Fig. 4, the vibration mode can be explained as follow. Solving the wave equation of the circular ring with respect to an extensional vibration mode, radial and circumferential displacements U_r, U_θ can be expressed[11] as

$$U_r = A\cos n\theta \cos \omega t$$
$$U_\theta = -nA\sin n\theta \cos \omega t \quad (1)$$

Where n, ω are number of nodal diameter and angular frequency of driving voltage respectively.

Superimposing the following two generated standing waves each other,

$$U_{r1} = A\cos n\theta \cos \omega t$$
$$U_{r2} = A\cos(n\theta - \pi/2)\cos(\omega t - \pi/2) \quad (2)$$

a traveling wave can be obtained.

$$U_r = A\cos(\omega t - n\theta) \quad (3)$$

The trace of particle motion at the surface or cylindrical shell, then is expressed as

$$(U_r / A)^2 + (U_\theta / nA)^2 = 1 \quad (4)$$

If a movable body is contacted to the inner or outer surface of the cylindrical shell, the body can be rotated through the friction force. If the inner or outer surface of the shell (stator) is threaded and the contacted body (rotor) is also threaded, the body can be rotate in the circumferential direction and moves in the axial direction when the traveling extensional wave is excited at the stator. To achieve the traveling wave at the stator, the stator must be excited the two degenerated vibration modes in accordance with equation (2).

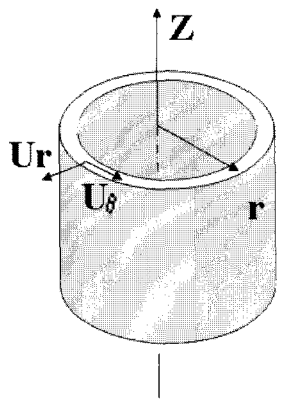


Fig. 4. Cylindrical coordinate for explaining the vibration mode.

The proposed piezopump is consisted of coaxial cylindrical shells that are bonded piezoelectric ceramic ring as similar to stator in Fig. 3. Traveling extensional waves at each elastic surface of coaxial cylindrical shells are established as stator surface of screw formed piezoelectric actuator in Fig. 3. Two traveling waves induced at each cylindrical shell, which have a spatial phase difference of $\pi/2$ radians (a half wavelength). Multiple chambers are formed between the crests of traveling waves at contact surface of two cylindrical shells. These chambers offer a platform for the transportation of capture fluid in the direction of the wave propagation as shown in Fig. 2. The peristaltic transferring action is not associated with any practically moving parts and the pumped liquids or gases are flowing with the traveling wave direction. The greatest feature of this piezopump is not required the valves because the peristaltic action of this piezopump produces to the tightly closed space that can be played an important role as a squeezing effect. As the voltage of piezopump is turned off, the sliding interface formed between two peristaltic stators against each other stops the flow of liquids, and then produces automatically a self-locking action as an absolutely closed operation of the conventional valves.

3. VIBRATION ANALYSIS AND PIEZOPUMP DESIGN

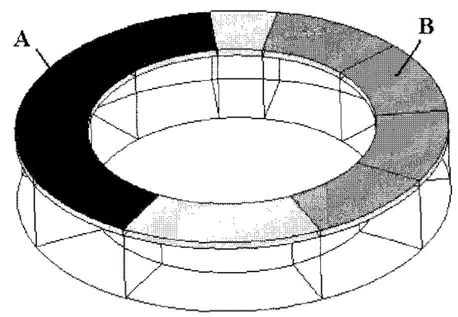
A numerical simulation of the piezopump was used to verify the operation principle. A modal and harmonic analysis of the proposed piezopump model was carried out for its design. Finite element modeling package ATILA was employed in the simulations.

The model was consisted of coaxial cylindrical metal shells bonded with annular type piezoelectric ceramic plates, which the outer shell was separated in two parts as shown in Fig. 5.

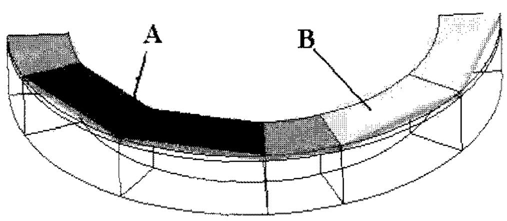
Properties of the materials used for the pump are listed in Table 1. Brass was used for the elastic body. From modal analysis results, it is determined that extensional resonance mode was B(0,5) and its operational frequency was 56.4 kHz.

Table 1. Piezoelectric and dielectric properties of the PZT-PMNS ceramic.

Items		Units	Measured value
Electromechanical coupling factor	k_p	%	58
Mechanical quality factor	Q_m		1500
Piezoelectric constant	d_{33}	pC/N	340
	d_{31}	pC/N	-120
Frequency constant	N_p	Hzm	2100
Relative dielectric constant	$\varepsilon_{33}/\varepsilon_0$		1300



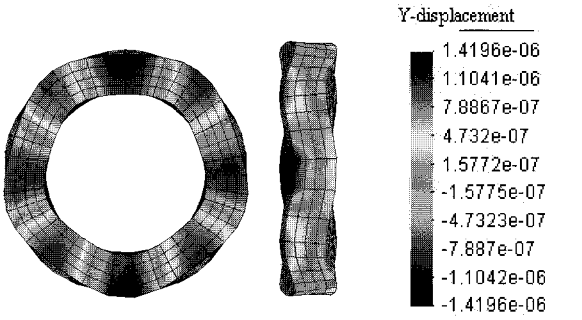
(a) Electrode pattern of inner cylindrical shell



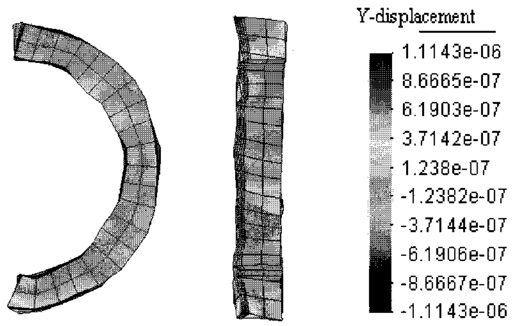
(b) Electrode pattern of outer cylindrical shell

Fig. 5. Electrode pattern of inner cylindrical shell.

Harmonic analysis was carried out to find out the distribution of the displacement. The results for the displacement distribution are shown in Fig. 6. The outer cylinder is separated in two parts, which is consisted of two semi-circles. Figure 6(b) shows the displacement at the separated outer shell. In this figure, we can find the fifth vibration mode B(0,5) at the circumference of the cylinders. The displacement at the outer surface of the inner cylinder, which is in intimate contact with outer cylinder, shows same pattern with the outer ones. The difference of the spatial phase is 180 ° between two patterns of displacements induced at the outer and inner cylinders, respectively. We also found out that a traveling wave was induced at the shells. In Fig. 6, the unit of Y-displacement value is meter. The distance between the crest and valley of the elastic wave traveling on the outer surface of the inner cylindrical shell is 2.8 μm, and the ones on the inner surface of the outer cylinder is about 0.8 μm. The driving mode is 5^{th} vibration mode and the peak voltage is 100 V.



(a) Displacement distribution of inner cylindrical shell



(b) Displacement distribution of outer cylindrical shell

Fig. 6. Displacement distribution of coaxial cylindrical shell.

4. PROTOTYPING OF THE PIEZOPUMP AND ITS PERFORMANCE

Based on the volume displacing mechanism using elastic traveling wave, and results of finite elements analysis, we made a pump and a sealing package. Piezoelectric ring was bonded to the inner and outer cylindrical metal shells, respectively. Silicon rubber was used to channel the fluid within the pump chamber. Components of a piezopump are shown in Fig. 7.

The piezoelectric ceramic was fabricated using a $0.9Pb(Zr_{0.51}Ti_{0.49})O_3$ – $0.1Pb(Mn_{1/3}Nb_{1/3}Sb_{1/3})O_3$ + $0.05Cr_2O_3$ composition[12] in order to make the piezopump used in this study. We used a conventional ceramic fabrication method. Its piezoelectric and dielectric properties are listed in Table 1. As shown in Fig. 5 and 7, the electrode on the piezoelectric ceramic ring is divided into two groups, 'A' and 'B' which are separated on a ring by a spatial phase difference of $\pi/2$ radians. Two phase voltage sources whose temporal phase difference is $\pi/2$ radians is applied to group 'A' and 'B' to drive the pump. Each group of electrode is also divided into several sections. Each section is polarized either positive or negative.

Inner cylinder	Inner diameter	20 mm
	Outer diameter	30 mm
Outer cylinder	Inner diameter	30 mm
	Outer diameter	40 mm
	Angle of arc	172 °

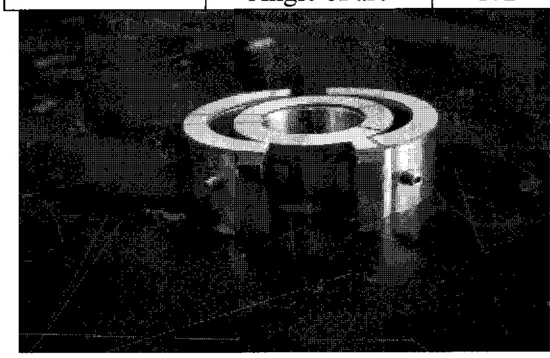


Fig. 7. Composition of a piezopump.

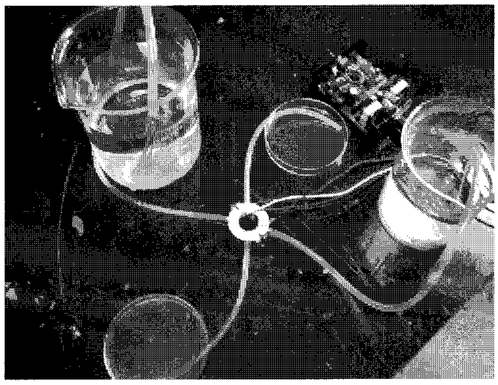


Fig. 8. Operation of prototype piezopump.

Figure 8 shows an operating pump while pumping water. The assembled pump was measured for its performance in terms of flow rate and highest pressure that the pump can reach. The flow rate of the pump was measured by collecting the water that was pumped in a given duration. The volume of the collected water was then measured using a mass cylinder. The highest pressure the pump can reach was measured by pumping water into vertical tube. The highest level that the water reached represents the highest pressure the pump can sustain. The performance is about 580 μl/min in flow rate, and highest water level reached is about 85 mm, which is equal to about 0.85 kPa, when the driving voltage is 150 V_p, 57 kHz. We confirmed that the flow direction can be changed easily by changing temporal phase difference between two voltage sources which applied to electrodes ‘A’ and ’B’.

5. CONCLUSION

A novel piezoelectric pump is proposed that is driven by traveling extensional waves on the interface of coaxial cylindrical shell providing a volume displacing mechanism. A piezoelectric ceramic ring was bonded to the cylindrical shell of the pump to induce traveling elastic wave along surface of the shell. The multi chamber between the peaks and valleys of the wave is formed at interface between the coaxial cylindrical shells which is in intimate contact with each other. The fluid can flow peristaltically along the wave. Components of piezopump were made, assembled, and tested to valid the concepts of the proposed pump and confirm the simulation results. The performance of the proposed piezopump is about 580 μl/min in flow rate with the highest pressure level of 0.85 kPa, when the driving voltage is 150 V_p, 57 kHz.

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