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A STUDY ON A PROGRESSIVE WAVE TYPE NOVEL PIEZOELECTRIC PUMP

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Abstract. *This study is about a novel small piezoelectric pump. The pump utilizes a thin vibration plate on which bimorph type piezoelectric actuators generate progressive wave. Usually, a normal piezoelectric pump needs check valves and sends fluid only in one direction. However the proposed pump doesn't use check valves and can send fluid to both forward and backward directions. In this report, principle of the proposed pump is described at first, and then examination by experiment and simulation is described. The authors prepare two types of the vibration plates which have different number of piezoelectric bimorph cells. Motion of the vibration plates in the air for sinusoidal drive with phase difference among the bimorph cells is investigated. Water flow generated by progressive wave on the vibration plate is also investigated by finite elements analysis. Characteristics of the pump are examined by experiments. As a result, effectiveness of principle of the pump with progressive wave is shown. Ability and problems of the experimental pump in the present condition are clarified.*

Keywords*: piezoelectric pump, bimorph cell, progressive wave, piezoelectric actuator*

1. Introduction

In the recent years, small size and light weight liquid pump is required in the various applications, such as water-cooled notebook type computer, portable automatic insulin injection system, and etc. There are also many studies about more miniaturized liquid pumps used as power sources for such as liquid driving micro machines or micro-total analysis systems (micro-TAS). In conventional small size pumps, some of them have limitation of miniaturization due to their mechanical structures or principles, and others send liquid with pulsation. Also some pumps cannot send large quantities of liquid by their principle, others cannot send liquid in both forward and backward directions. High efficient, more functional and high performance small pumps are required in the engineering field.

In this study, novel piezoelectric pumps using thin metal shim plates on which plural piezoelectric bimorph cells generate progressive wave are proposed and investigated. Purpose of the study is to develop the novel piezoelectric pump using progressive wave. Some of the authors have already presented about principle of the pump and introduced three types of the thin plates (Henmi *et al.* 2003). In the present paper, two of the thin plate types are made experimentally, and characteristics and performance of the experimental pump using the plates are investigated. Some computer simulation results about water flow caused by model of the vibration plate are also shown.

2. Principle of the pump

Figure 1 shows principle of the proposed piezoelectric pump. A thin plate which is fixed in flow direction is inserted into flow path and progressive wave is generated on the plate by piezoelectric actuators. Liquid around the plate are carried by the progressive wave. This is outline of the pump principle.

Some pairs of piezoelectric elements are attached onto a thin metal shim plate, thus plural piezoelectric bimorph cells are composed on the single metal shim plate. We call the composition of the thin metal shim plate and the piezoelectric elements as “vibration plate” in this study. The vibration plate is inserted into flow path, and progressive wave is generated on the plate by motion of a series of the bimorph cells. Liquid between the vibration plate and flow path wall is carried on the progressive wave.

Since the pump uses progressive wave, the flow is very smooth. Flow can easily change in forward and backward directions by changing phase of actuator drive. Though driving frequency is limited by mechanical characteristics of the vibration plate, flux can be changed by changing either frequency or amplitude of the progressive wave. Since the piezoelectric bimorph cells are soaked into liquid, the whole vibration plate must be waterproofed.

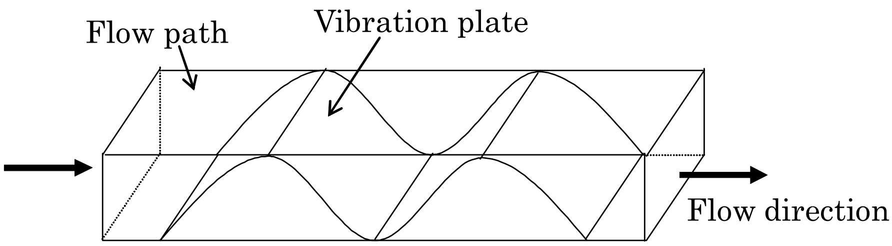


Figure 1. Principle of the proposed pump

Figure 2 shows motion of the vibration plate which has four pairs of the piezoelectric bimorph cells. One side of the vibration plate is fixed on wall of the flow path so that the plate itself doesn’t move along carrying direction. Accordingly, progressive wave occurs along another side of the vibration plate.

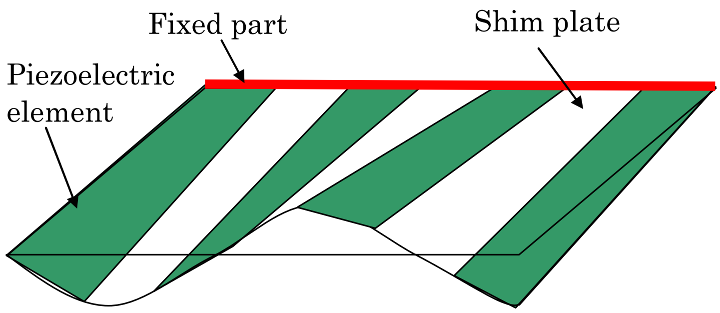
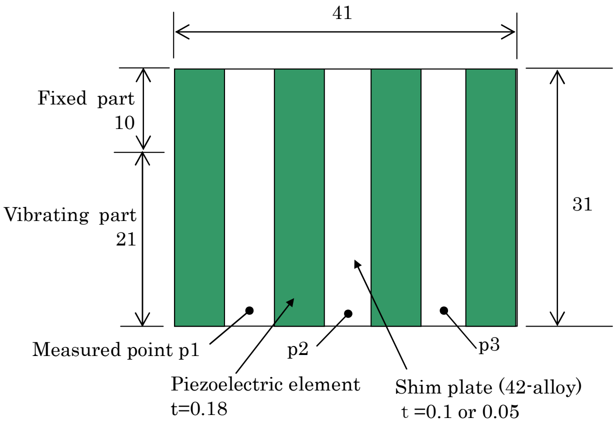


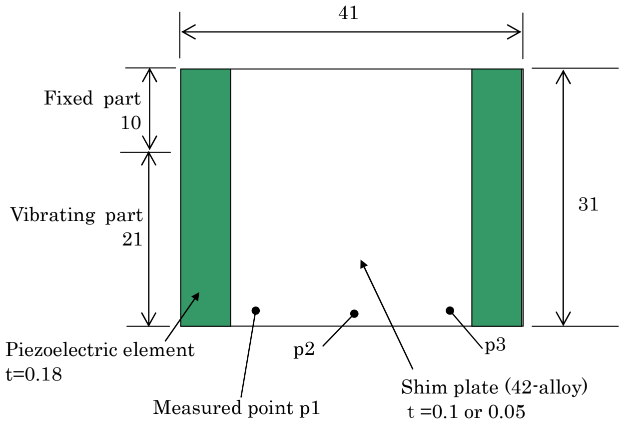
Figure 2. Schematic of the vibrating plate

3. Experimental devices

Figure 3 shows dimensions of the actual vibration plates made experimentally. The vibration plates shown in (a) and (b) use four and two pairs of piezoelectric elements respectively. They are called (a) four series type and (b) two series type respectively in this study. Though these two kinds of vibration plate are chosen this time, any plural number of bimorph cells can be possible to generate progressive wave on a vibration plate. Also two kinds of shim plate of different thickness, 0.05mm and 0.1mm, are prepared for each type of the vibration plate. Piezoelectric elements of 0.18mm thickness are attached on both sides of the shim plate surface. Size of shim plate as well as number of bimorph cell can make change in compliance with desired performance or required limitation.

Length of fixed part to flow path is 10mm. Length of outthrust part, i.e. vibrating part is 21mm. Point P1, P2 and P3 near free end on the shim plate are measurement points. As the vibration plate is soaked into liquid, whole plate are coated by waterproof resin. Also flexible film of 50μm thickness which is not shown in the Fig.3 is attached on the half part of the plate near the free end and thrusts out around the plate in order to avoid escaping liquid between both sides of the vibration plate surface.





(a) Four series type vibration plate (b) Two series type vibration plate

Figure 3. Dimensions of the vibration plate

Figure 4 is a photo of the pump assembly showing that the vibration plate is set into the pump case. The pump case is made of acrylic resin so that status of liquid flow can be observed. Height of the flow path where the vibration plate is inserted is from 0.1mm to 0.4mm excluding thickness of the plate. It is changed with spacer sheets. Ink pocket exists both before and after flow path of the vibration plate in order to visualize liquid flow.

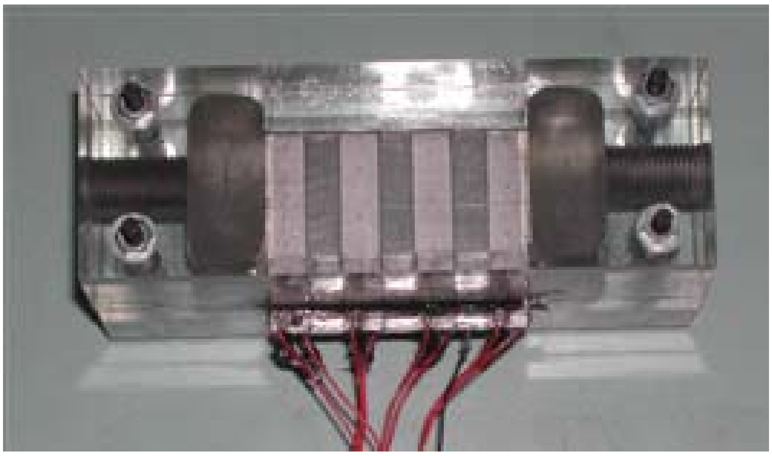


Figure 4. Schematic view of the experimental pump assembly

4. Experimental results

4.1. Behaviour of the vibration plate

When the bimorph cells drive sinusoidally with phase difference, the vibration plate behaves like Fig.5. The figure shows results of the free end displacement of the 0.1mm four series type vibration plate. As it is impossible to measure motion of the plate in the water, the plate is fixed in the air by a cramp, and then the measurement points P1, P2 and P3 on the shim plate are measured by eddy current type non-contact displacement sensors. The figure is for the conditions that phase difference of sinusoidal drive between adjoining actuators is 90 degrees and that driving frequency is 100Hz. It shows that the phase difference P1 and P2, or P2 and P3 are about 90 degrees and thus that progressive wave proceeds from P3 to P1 correctly. For these driving conditions, displacement amplitude of the sinusoidal wave are about $50\mu m_{p\text{-}v}$ at P2 and about $80\mu m_{p\text{-}v}$ at P1 and P3. This vibration behavior changes in response to driving frequency, phase difference between each bimorph cells, and thickness of shim plate. Behaviors of the vibration plates are experimentally investigated in various driving conditions.

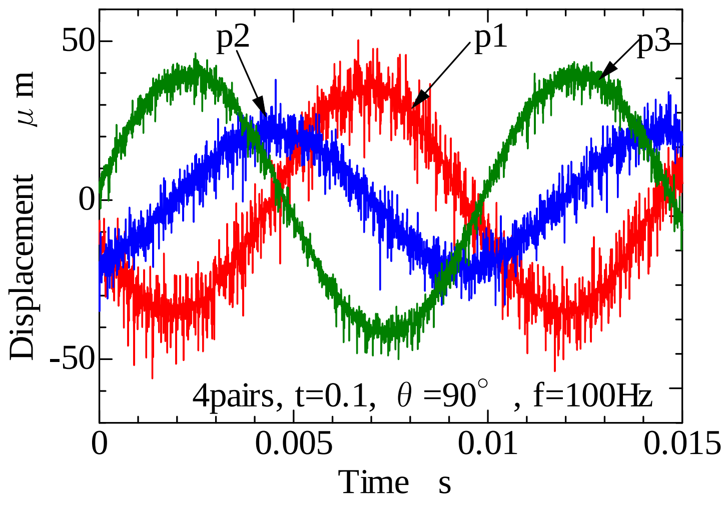


Figure 5. Behavior of vibration plate (f=100Hz, θ=90°)

Figure 6 shows amplitude and phase at the measurement points of 0.1mm hour series type vibration plate under conditions that phase between adjacent bimorph cells are 90° and that driving frequency is from 100Hz to 550Hz. Value of phase is denoted as phase difference from input sinusoidal signal to a side bimorph cell near P3. From the figure, every phase value of P1, P2 and P3 increase with the same constant rate from 100Hz to 300Hz. Amplitude values are almost constant in some degree for any frequency except for around 400Hz and 500Hz. This is because first and second order natural frequencies exist on about 380Hz and 540Hz respectively. The first and second order vibration mode shapes are shown in Fig.7.

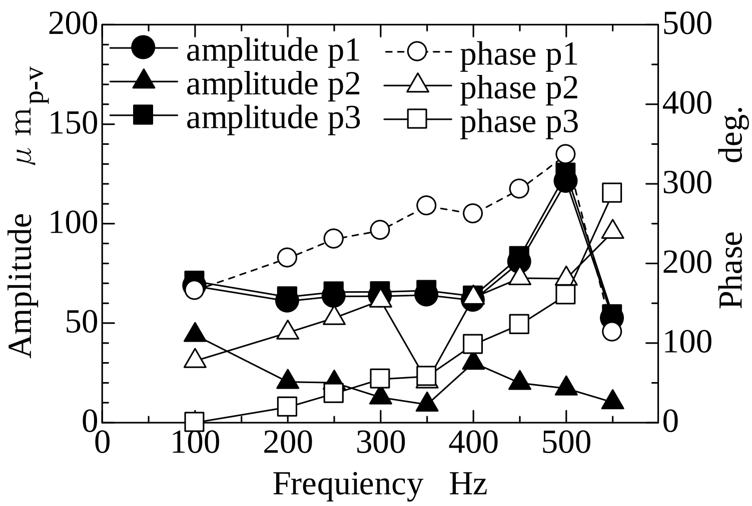
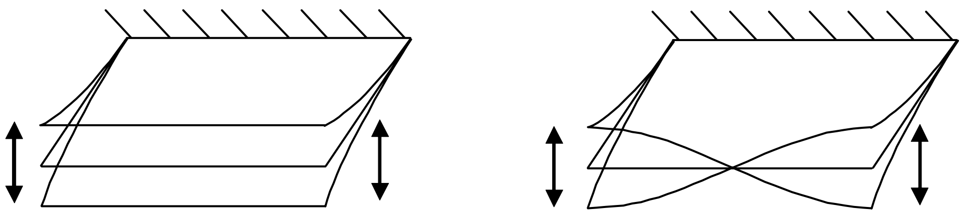


Figure 6. Amplitude and phase of sinusoidal motion at point p1-p3



(a) First order vibration mode (b) Second order vibration mode

Figure 7. Mode shape of vibration plate for free vibration

4.2. Experimental results of water flow

On the basis of the experimental results of vibration plate response in the air, some driving conditions are selected. The vibration plate is inserted into the pump case, and height of the flow path is adjusted. Then liquid flow experiments using water as driven liquid are executed actually. Status of water flow is observed by naked eyes and CCD camera using black ink for visualization. Water flow is investigated for driving frequency from 50Hz to 500Hz, and for phase difference from 15° to 90°. It is found that water flows well under several conditions. For the 0.1mm four series type vibration plate, the same driving conditions with the ones of Fig.5 and 6, i.e. driving frequency 100Hz and phase 90°, are fairly good conditions. Estimated flux is about 3ml/min. under the conditions. It is calculated from dimensions of flow path and speed and width of ink flow observed from video image. Figure 8 shows the image of water flow visualized by black ink. It can be observed that black ink flows from left side to right side of the image. The photo is taken at the beginning of pump drive.

The amount of flux is enough to use in micro-TAS, but not applicable yet to water cooled notebook computer or insulin pump, etc. Also flux changes by state of assembly of the experimental pump case even under the same driving conditions. Pump case needs to be redesigned so that height of flow path can be changed with finer resolution and so that the pump case can be assembled with higher positioning accuracy every time.

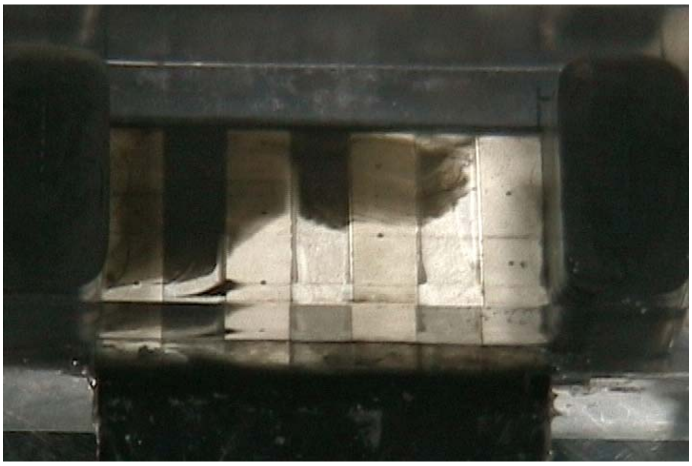


Figure 8. Image of flow at the beginning of pump drive

5. Simulation of water flow

In order to investigate how much flux can be obtain, water flow caused by motion of vibration plate is calculated with FEM simulation. Figure 9 shows schematic view of cross section of flow path along flow direction. Hatched part is modeled in the simulation. The simulation is executed under two dimensional FEM. In the present report, motion of the vibration plate is given as a sinusoidally moving boundary, not caused from inverse piezoelectric effect. Displacement of the moving boundary is given by Eq. (1) that shows progressive wave.

$$y = h_0 + A\sin\left(2\pi ft - 2\pi \cdot \frac{x}{L} \cdot n\right) \tag{1}$$

where y is displacement perpendicular to flow direction, h_0 is height of center of sinusoidal motion, f is driving frequency, t is time, L is length of vibration plate, x is position in flow direction and n is constant determined from shape phase of given progressive wave between both ends of the plate. The amplitude A is given as 100μm. Flow velocity is calculated under several shape phases of progressive wave between both ends of the vibration plate. Driving frequency is set at 100Hz.

Figure 10. shows a simulation result which is a instant image for motion of four series type vibration plate. Flow velocity vectors are shown in the result. The result is calculated for the shape phase of 180°. The progressive wave goes from left side to right side of the figure. It can be observed that most of the velocity vectors turn right but some of them turn left. It means that flow in the pump is not so simple.

Flux is estimated using the amount of vector component in the flow direction and instant cross section area of the both ends of flow path under the vibration plate. The estimated flux for the result in Fig.10 is about 11ml/min. Amounts of estimated flux which are obtained from simulation are from 4ml/min. to 12ml/min. for several driving conditions. These values are larger than the experimental results. The main reason why actual experimental pump flow worse than simulation is that the model of the vibration plate, i.e. moving boundary, can move compulsorily with the same vibration amplitude in the air in spite of existence of water resistance force. Influence of the flexible film avoiding liquid escape between both sides of the vibration plate surface. Namely the results of simulation tell us that large flux can obtain if the vibration plate can generate larger amplitude in water.

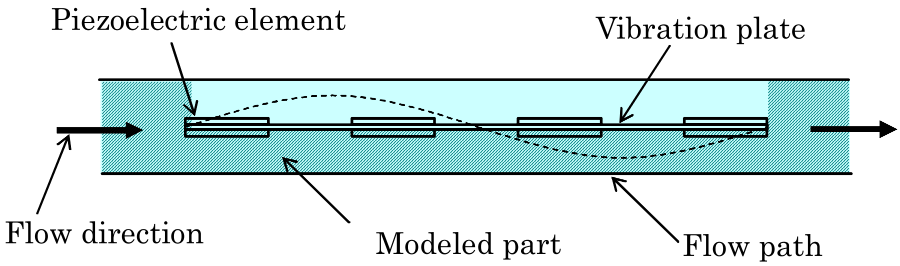


Figure 9. Schematic view of flow path cross section

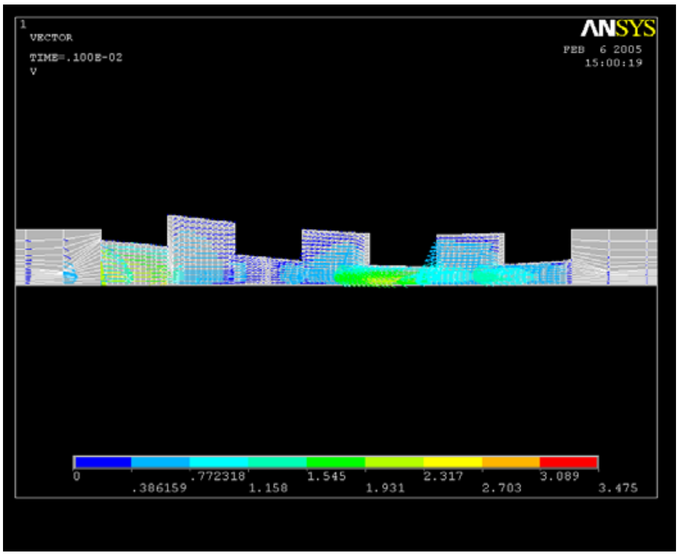


Figure 10. Example of simulation result image (flow velocity vector)

6. Conclusions

In this paper, a novel piezoelectric pump which used progressive wave of vibration plate in flow path was introduced and made experimentally. The principle of the pump was also explained. Behavior of the vibration plate driven in the air was investigated and it was shown that progressive wave was well generated on the vibration plate by bimorph cells' drive. Water flow experiments were executed. Water flow was observed with black ink visualization and effectiveness of the pump principle was proved experimentally. Amount of flux obtained experimentally was enough for micro-TAS but not enough for water cooled notebook computer or insulin pump yet. Flow simulation was executed using 2D-FEM. Flux was estimated using the simulation result and it was larger than experiments. Simulation results showed that vibration plate needed to generated larger amplitude in order to obtain more flux.

7. Acknowledgements

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4. References

Henmi, N., Tamura, T., Tanaka, H., Tanaka, M., 2003, "A Study on a Progressive Wave Type Miniaturized Piezoelectric Pump", Proceedings of the Annual Meeting in Autumn of the Japan Society for Precision Engineering, CD-ROM, Toyama, Japan, pp. 638, (in Japanese).