PIEZOELECTRIC MICROMIXER USING A SWIRLING MOTION

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ABSTRACT

We propose a piezoelectric micromixer that generates the unidirectional rotation of a liquid inside the hole of a metallic cube, the side length of which is a few millimeters. The simple cubic structure of the micromixer is easy to be fabricated and the miniature size is suited for portable medical devices. In this report, we built the prototype of the micromixer comprised of a metallic cube (a side length of 5 mm) with a hole (diameter of 3 mm). The prototype generated water movement of 5 rps inside the hole by applying AC voltages of 60 $V_{p\text{-}p}$ and 275 kHz in experiment.

KEYWORDS

Piezoelectric Actuator, Ultrasonics, MicroTAS, Lab on a chip, CFD analysis

INTRODUCTION

A technology that mixes a few drops of a liquid is required for Micro Total Analysis Systems (µTAS) and Lab on a Chip [1-3]. The use of a micromixer has advantages such as small amounts of sample and reagent, short time reaction, lower cost and high throughput, especially in the field of analytical chemistry and life science. Principles of active mixing are proposed, such as pressure difference, ultrasonic [4], acoustic [3], electrokinetic [5], magneto-hydrodynamic [6], and micro magnetic stirrer bar [7]. These devices are succeeded in mixing a small amount of a liquid, but the structure of the devices is complicated.

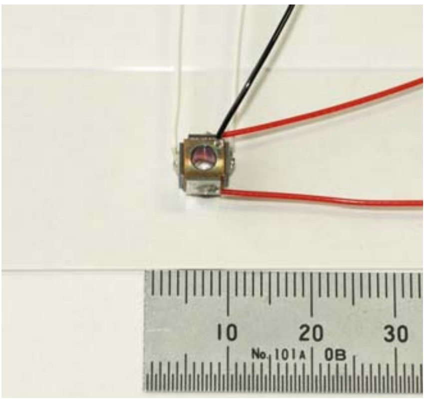

Figure 1. Piezoelectric micromixer

We propose a piezoelectric micromixer that generates the unidirectional rotation of a liquid inside a hole of a metallic cube, the side length of which is a few millimeters (Figure 1). The rotation mixing is one of the most efficient and uniform method for mixing a liquid; in fact, practical devices uses rotation as a mixing method, such as a magnetic stirrer. The micromixer comprises of a metallic cube with a through-hole and four piezoelectric elements are bonded to four sides. When AC voltages are applied to the piezoelectric elements, the liquid filled in the hole is rotated by the vibration of the piezoelectric elements. The advantages of the micromixer are: (1) the structure is very simple and miniature. The simplicity is easy to be fabricated and the miniature shape is suited for portable devices (2) The micromixer can rotate a liquid through a plastic wall as long as the inside of the micromixer and the plastic wall are contacted. Operators can replace a plastic cell easily and the use of cells prevents a contamination.

DRIVING PRINCIPLE

The proposed micromixer uses a first bending vibration mode [8] that bends the center axis of the through-hole. When two first bending vibration modes with a temporal phase difference of $\pi/2$ degrees are generated as shown in Figure 2, the center hole generates a unidirectional swirling motion (counterclockwise direction from the top view). This swirling motion transfers a mechanical energy to a liquid by a viscosity and the liquid rotates circumferentially. This driving principle has been used for driving a micro piezoelectric actuator [9].

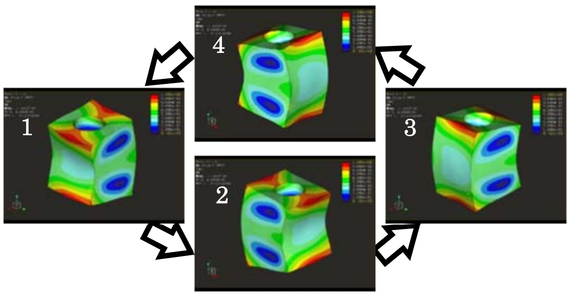

Figure 2. Driving principle

When an AC voltage with the natural frequency of the vibration mode is applied to a piezoelectric element, the first bending vibration mode is excited by expansion and contraction of the piezoelectric element. To rotate the liquid inside the micromixer, two AC voltages with temporal phase distance of $\pi/2$ are applied: $E_1 = A\sin(2\pi\ f_r t)$ and $E_2 = A\sin(2\pi\ f_r t + \pi/2)$, where A is amplitude, f_r is frequency of the AC voltages. Also, f_r is the natural frequency that excites the first bending vibration mode.

COMPUTATIONAL ANALYSIS

The natural frequency of the first bending vibration mode is clarified by finite element method (FEM) modal analysis, and the flow of the liquid is estimated by a computational fluid dynamics (CFD) analysis. Figure 3 shows the design of the micromixer and the mesh model of a modal analysis. The shape of the micromixer is a cube with side length of 5 mm with a through-hole of 3 mm at the center. The model parameters for the analysis are those of a phosphor bronze (Young's modulus 113 GPa, Density 8.81×10^3 kg/m^3, Poisson ratio 0.34) In the result, the first bending vibration mode occurred at approximately 250 kHz.

The CFD analysis software (Flow-3D, FLOW SCIENCE Inc) is used for estimating a flow generated by the

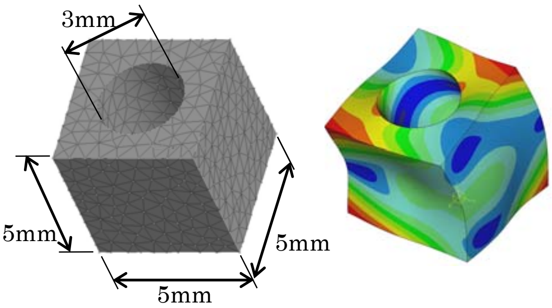

Figure 3. Model of the micromixer (left) and the result of FEM modal analysis (right)

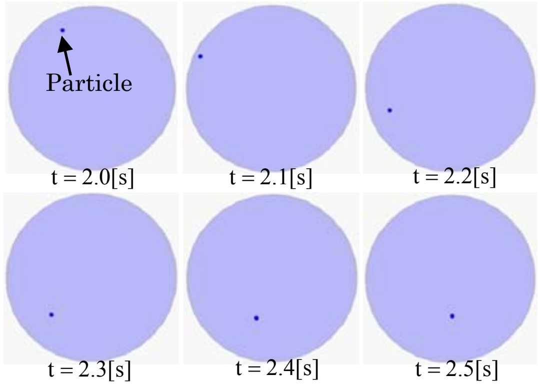

Figure 4. CFD analysis result

micromixer. In the analysis, forces that correspond to the two AC voltages are applied to the sides of the micromixer. (The high frequency makes the computation time long, so the frequency of the applied force is 140 Hz in the simulation.) A liquid (water) is filled in the through-hole and a particle floats on the water surface. Figure 4 shows that a particle rotates counterclockwise on the water surface in the 3-mm hole during 2.0 to 2.5 s from the start.

PROTOTYPE MICROMIXER & EXPERIMENTAL

The micromixer was built as shown in Figure 1. Four piezoelectric elements are bonded to the sides. A ground line is connected to the metallic body by a conductive adhesive. A transparent slide glass is bonded to the bottom of the micromixer by a flexible adhesive to prevent a leak of a liquid.

An impedance characteristic clarifies the resonant frequency of the prototype. Figure 5 shows the frequency response of the impedance measured by a LCR meter (3532-50, Hioki E. E. Corp.). A resonance (sharp change of the impedance) is observed at approximately 275 kHz. The error between the FEM estimation and the measurement result is about 10%. The value of the bottom peak is approximately 0.5 kΩ.

The mixing performance of the micromixer is examined by measuring the rotational speed of the liquid. A experimental setup is shown in Figure 6. The micromixer is placed on a transparent plate and water is filled inside the through-hole as the liquid. The volume inside the through-hole is approximately 0.035mL that is almost equal to the volume of a drop of water. An aluminum powder is floated on the water surface as tracer particles and a light source illuminates the micromixer from the bottom side. A video camera is installed at the top side of the micromixer and captures the movement of the particles. Fig. 6 right shows a view captured by the video camera, in which the aluminum powder is seen as black particles.

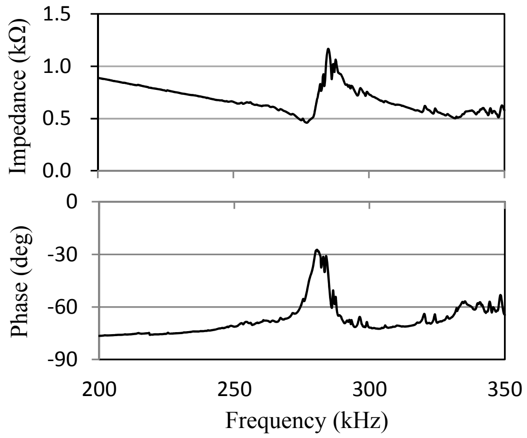

Figure 5. Impedance characteristic of the micromixer

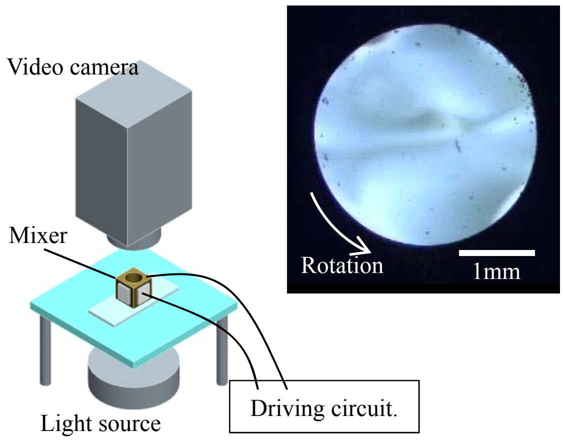

Figure 6. Experimental setup

RESULT & DISCUSSION:

The water starts to rotate inside the hole when the two AC voltages are applied to the piezoelectric elements. Figure 7 is a time history by tracking the movement of a particle at the applied voltage of 60 $V_{p\text{-}p}$ and the frequency of 276.5 kHz. The particle is driven up to approximately 5-6 rps. The upper side of Figure 7 shows the movement of a particle (Particle *A*) captured by the video camera. The particle *A* was selected as the fastest one and it rotates. As for the other particles, the displacement of the particles decreases as approaching to the wall of the inner surface. For example, particle B is much slower than particle A. It is due to that the viscosity of the water increases near the wall.

In the further study, we confirmed following two behaviors of the micromixer: (i) the rotational speed is in roughly proportion to the magnitude of the voltages. (ii) The rotational direction is reversible when the two AC voltages are switched. The reversed rotational speed obtained is almost equal to the original speed.

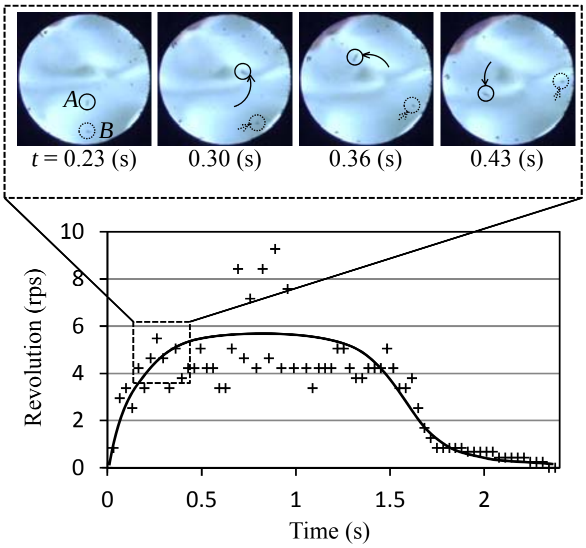

Figure 7. Time history of the rotation

CONCLUSION

In this paper, we demonstrated that the piezoelectric micromixer generates the rotation of water using the first bending vibration mode of a metallic cube. The prototype mixer was fabricated as a cube (a side length of 5 mm) with a through-hole (3 mm in diameter). The experiment shows that a drop of water (approximately 0.035 mL) was driven up to 5 rps inside the hole of the micromixer.

In the future, we will clarify the fluidic mechanism from the swirling motion to the generation of the flow by using a CFD analysis for pursuing the optimal design methodology of the micromixer. Another important aspect of the development is the prevention of a contamination. Use of a disposable plastic cell inside the micromixer is effective. Operators can replace the plastic cell easily and the use of the cells prevents a contamination. In a pre-experiment, we confirmed that the micromixer can rotate water through a plastic wall as long as the inside of the micromixer and the plastic wall are contacted.

Although the micromixer has not been optimized yet, the experimental result is already practical due to its enough mixing power. Mixing for an environment analysis device such as spectrophotometer would be one of the potential applications in industry.

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