ACOUSTIC ENERGY HARVESTER UTILIZING A MINIATURE ROTOR ACTUATED BY ACOUSTICALLY OSCILLATING BUBBLES-INDUCED SYNTHETIC JETS

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ABSTRACT

This paper presents a new type of acoustic energy harvesting technology where a miniature rotor actuated by acoustically oscillating bubbles-induced synthetic jets makes piezocantilevers periodically vibrate to generate electric power. The presented energy harvesting technology can extract mechanical power from acoustic energy using an acoustically driven miniature rotor in an aqueous medium and convert the mechanical power to electric power for wireless devices. This new type of actuation technique is a simple but useful tool not only for the energy harvesting but also potential acoustic wave sensors.

INTRODUCTION

Wireless sensor networks (WSNs) have been recognized as one of the world's top technologies in the 21st century because the WSNs have suggested attractive solutions for various industrial applications such as national defense, environment monitoring, health care, and industrial monitoring. With increasing demand of WSNs, the development of power sources for the WSNs has been becoming significantly important. The WSNs normally consist of multiple low-power ubiquitous microsensors aimed to operate for a semi-permanent period. For the power sources of these microsensors, a chemical battery has been typically employed by now. However, the chemical battery is very limited to be vastly used for WSNs due to its size, maintenance, and bio-incomparability [1-3].

Hence, energy harvesting technologies, collecting energy from natural or artificial sources and storing it for later use, have received the worldwide attention as an alternative to the conventional battery. Numerous energy harvesting technologies have been developed, and classified according to their energy sources - solar, mechanical, temperature gradient, dynamic fluid, acoustic, and magnetic [3-5].

Especially, the acoustic energy harvesting is a method generating the electrical energy from acoustically induced mechanical vibration. In spite of comparatively lower power density than other energy source technologies, the acoustic energy harvesting technology has been recognized as a promising power source for the WSNs because the energy source is not only clean and sustainable but also vastly available in our daily life [6, 7].

Recently, Yang et al. presented a triboelectrification -based thin-film nanogenerator for harvesting acoustic energy from the ambient environment. The thin-film nanogenerator was structured using a polytetrafluoroethylene thin film and a holey aluminum film electrode. When the thin-film oscillates due to the acoustically initiated pressure difference on its two side, it could generate the electrical energy by triboelectric effect between the films [7]. Lee et al. developed a novel acoustic energy harvester based on the dynamic behavior of an acoustically excited oscillating droplet attached on a piezocantilever. When a droplet on a piezocantilever is oscillated under acoustic excitation, its oscillation produces the periodic bending motion of the piezocantilever, resulting in the generation of an electric power [8].

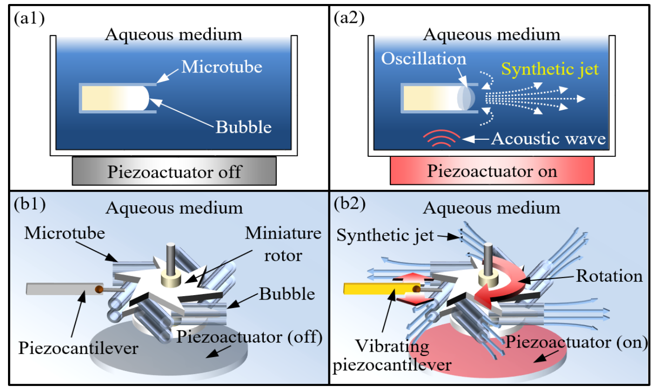

Figure 1: (a) Sequential sketches of the inducement of synthetic jet; (b) Schematic diagram of an acoustic energy harvester utilizing a miniature rotor actuated by acoustically oscillating bubbles-induced synthetic jets. Twelve bubbles in microtubes of the same size are integrated with the miniature rotor.

In this paper, a new type of acoustic energy harvesting technology where an acoustically driven miniature rotor makes single or multiple piezocantilevers vibrate to generate electrical energy is proposed in Fig. 1. The proposed energy harvesting system mainly consists of a miniature rotor actuated by acoustically excited oscillating bubbles-induced synthetic jets and a piezocantilever converting the mechanical vibration of the piezocantilever to the electrical energy.

When compressible bubbles in microtubes are acoustically excited at the natural frequency of the bubbles which is a function of the bubble length, the bubbles periodically oscillate back and forth in the tubes and simultaneously induce synthetic jets providing the propulsion force which makes the miniature rotor rotate [9-11]. Under the acoustic excitation, the miniature rotor continuously rotates and provides fine mechanical vibration to the piezocantilever which is initially set up beside the rotor tips. Consequentially, electrical energy is generated due to the piezoelectric effect and stored via an electric circuit.

FABRICATION AND EXPERIMENTAL SETUP

Figure 2 shows the schematic exploded diagram of a miniature rotor for acoustic energy harvesting as well as the images of the prototype of the rotor. The prototype of the miniature rotor consists of a supporting frame, two rotor bodies, six pairs of tubes with one close end, a metallic bushing penetrating the center of the two rotor bodies, and a center axis.

To stably hold a gaseous bubble in a microtube and obtain the high mobility in an aqueous medium, the inner surface of the microtubes and the rotor bodies have to be hydrophobic [12]. So that, Teflon and acrylate are chosen for the materials of the microtube and the rotor bodies, respectively. The rotor bodies are manufactured by using a laser cutter (IS-640, Innosta Co.). The bushing is inserted in the center holes on the rotor bodies to provide the bearing surface between the rotor bodies and the center axis pinned on the supporting frame. UV epoxy is used to glue each pair of Teflon tubes onto the bottom rotor body. Commercial products are used for the Teflon tubes (inner diameters and length: 400 μm, 2 mm, respectively) and the bushing.

The schematic diagram of the experimental setups is shown in Fig. 3. The setup mainly consists of electrical and optical systems. A disk type piezoactuator (MFT-27T -4.1A1 KEPO Co.) is operated by a function generator (33210A, Agilent Co.) and a voltage amplifier (PZD700, Trek Co.) to apply an acoustic wave to the miniature rotor. All experiments are conducted in a water chamber (5 (L) × 5 (W) × 2 (H) cm³). Test images are obtained by using a charge-coupled device camera (EO-1312C, Edmund Optics) or high-speed camera (Phantom Miro eX4, Vision Research Inc.) integrated with a zoom lens (VZMTM 450i eo, Edmund Optics) and saved on a personal computer. Generated voltages from the energy harvesting system are measured with a digital oscilloscope (TDS3012, Tektronix, Inc.).

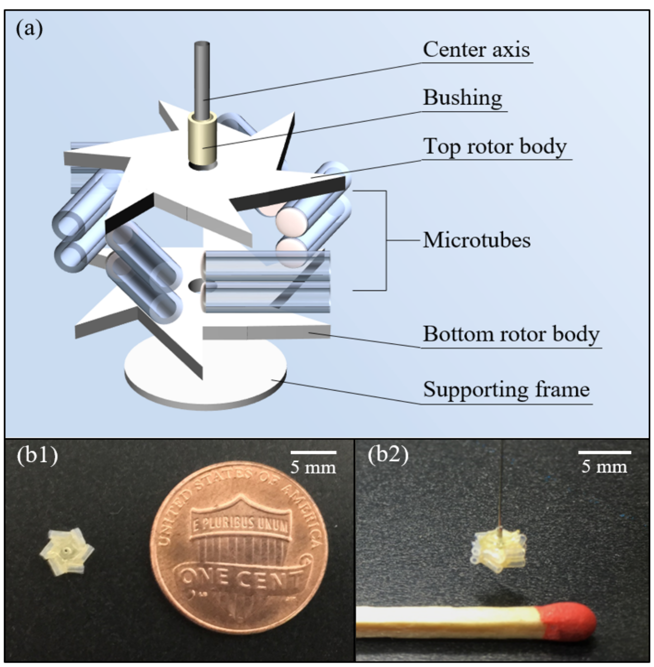

Figure 2: Schematic exploded diagram of the proposed miniature rotor and the images of the prototype miniature rotor.

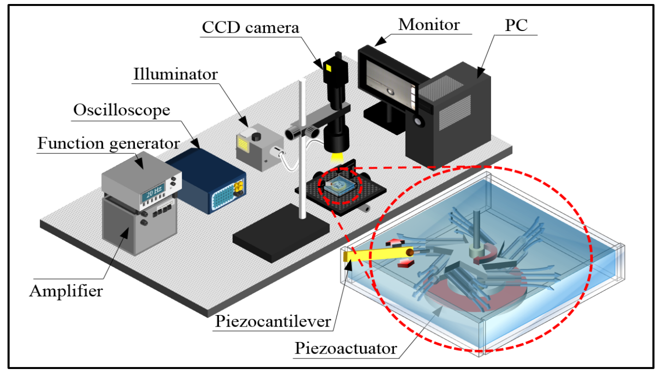

Figure 3: Schematic diagram of experimental setup.

EXPERIMENTAL RESULTS

In order to prove the concept of an acoustically driven miniature rotor, the behavior of an oscillating bubble actuated under acoustic excitation and an oscillating bubble-induced synthetic jet is experimentally investigated by high-speed images and μPIV (microParticle Image Velocimetry), respectively. When a Teflon tube is submerged into an aqueous medium, a column shaped compressible bubble (length: 1.7 mm) is automatically trapped in the tube. The natural frequency of the bubble is experimentally found at 2.15 kHz. To verify the synthetic jet induced by an acoustically excited oscillating bubble in a tube, flow visualization is performed using a 532 nm laser light (MGL-H–532 nm, Changchun New Industries Optoelectronics Tech Co.) to illuminate fluorescent particles (15 μm dia., FF1015-01, Fluostar, EBM Co.) which are

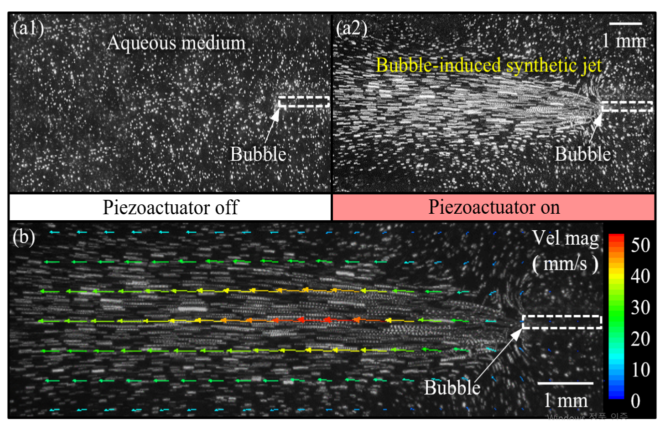

Figure 4: (a) Synthetic jet induced by an acoustically excited oscillating bubble at its natural frequency; (b) μPIV result of the flow fields.

initially seeded in an aqueous medium. When the bubble in the Teflon tube generates a synthetic jet under acoustic excitation by the piezoactuator attached beneath a water chamber, the flow field of the synthetic jet is visualized, as shown in Fig. 4. The white lines traced by the particles apparently show the pattern of the unidirectional flow of the synthetic jet in Fig. 4(a). Based on the captured high-speed images, μPIV is conducted using a commercial software (Insight 4G™). The result is plotted in Fig. 4(b). Note that the maximum flow velocity (51 mm/s) occurs 2.5 mm away from the opening of the tube.

To investigate the motion of the miniature rotor driven by the acoustically induced synthetic jets, the rotating speed of a miniature rotor is measured as RPM (revolutions per minute) in different acoustic frequencies and distances from a piezoactuator. The RPM of the rotor is highly dependent on the applied acoustic frequency and inversely proportional to the distance from the piezoactuator which clearly shows that the miniature rotor is actuated by an acoustic wave. The maximum RPM of the rotating rotor (154 RPM) is obtained at the bubble's natural frequency (2.15 kHz) where the strongest synthetic jets occur. Note that during the measurement of the rotating speed with respect to the distances from a piezoactuator, the miniature rotor is actuated at the natural frequency of the bubbles. The proposed energy harvesting technology is tested using a custom-made piezocantilever. The snapshots of a stationary and rotating miniature rotor for energy harvesting are shown in Fig. 5, respectively.

The electric voltage generated from the vibrating piezocantilever is measured at different frequencies and times. The generated voltage strongly relies on the applied frequency as the rotating speed of the rotor. But unlike the rotating speed of the rotor, the generated voltage is only properly measured around the natural frequency of the bubbles where the propulsion force generated by the acoustically induced synthetic jet is strong enough to make the piezocantilever vibrate. While the bubbles trapped in the rotors are acoustically excited at the natural frequency of the bubbles, the miniature rotor continuously rotates and generates the voltage (around 62 mV) for overall actuation time.

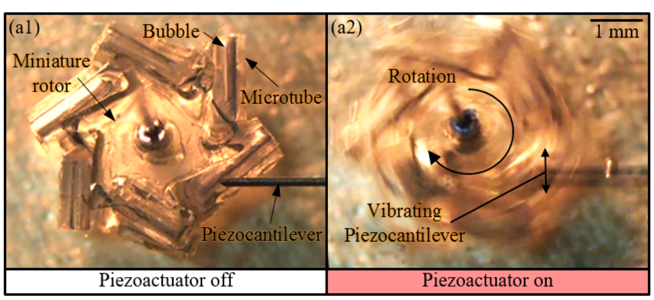

Figure 5: Snapshots of a stationary and rotating miniature rotor for energy harvesting.

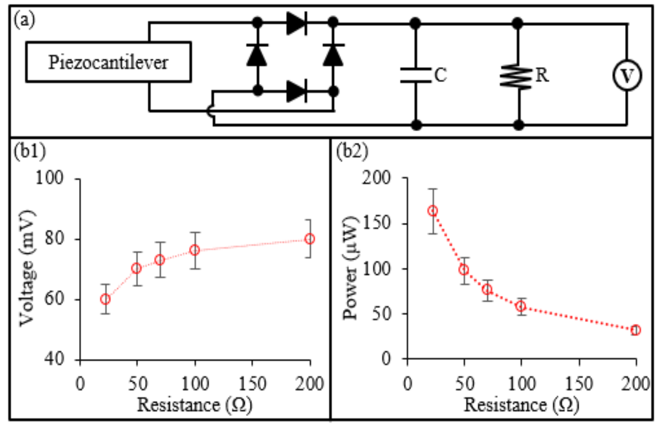

Figure 6: (a) Custom-made electrical circuit mainly consisting of voltage rectifier and load; (b) Measurement of the output voltage and power generated from a vibrating piezocantilever using the custom-made electrical circuit.

A custom-made electrical circuit is used to rectify the alternating current (AC) signal generated from the vibrating piezocantilever. The electrical circuit is a full-wave-bridge type rectifying circuit consisting of four Schottky diodes, as shown in Fig. 6(a). The output voltage and power generated from the piezocantilever are measured using the electrical circuit with different electric loads. As the electric load increases, the output voltage and power increases and decreases, respectively. The maximum power for the load (10 Ω) was measured to be about 165 μW at the natural frequency of the bubbles.

As proof of concept, storage capacitor charging tests are performed for 0.1 μF and 1 μF capacitors. The electrical circuit for energy storage is obtained by switching the electrical load to a capacitor on the electrical circuit. The charged voltage is measured while the rotor is actuated at the natural frequency of the bubbles. The result indicates that the charged voltage for 1 μF capacitor is higher than the charged voltage for 0.1 μF capacitor; on the other hand, the saturation time (about 60 s) for 1 μF capacitor is longer than the saturation time (about 35 s) for 0.1 μF capacitor. The maximum charged voltages on the 0.1 and 1 μF capacitors are 162 and 197 mV, respectively.

Finally, in order to demonstrate the possibility of improving the electric energy density provided by the proposed energy harvesting technology, the effect of multiple piezocantilevers on the electric energy density is studied. The snapshots of a stationary and rotating miniature rotor for energy harvesting using two piezocantilevers are shown in Fig. 7(a). The sum of the generated voltages from each vibrating piezocantilever during the actuation time of the miniature rotor is measured and plotted in Fig. 7(b). The sum of the generated voltages from two piezocantilevers is almost doubled as compared with a single piezocantilever.

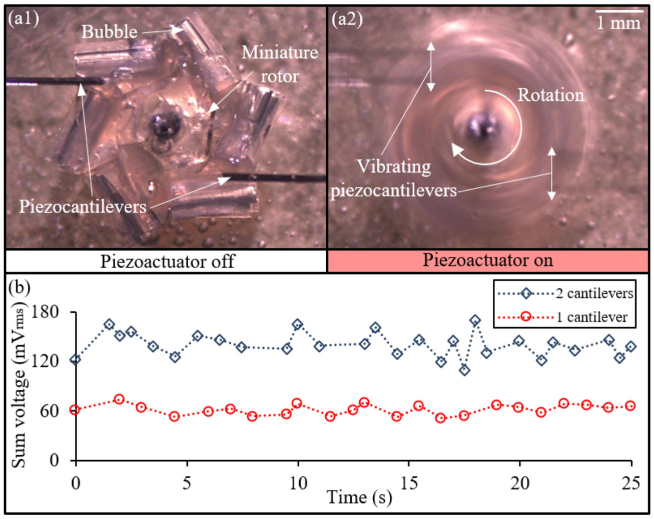

Figure 7: (a) Snapshots of a stationary and rotating miniature rotor for energy harvesting with two piezocantilevers. (b) Measurement of the sum of the generated voltage from two vibrating piezocantilevers and one vibrating piezocantilever with time variables at the bubble's natural frequency (2.15 kHz).

CONCLUSION

A new type of acoustic energy harvesting technology utilizing a microrotor actuated by acoustically oscillating bubbles-induced synthetic jets has been developed. First, the behavior of an oscillating bubble under acoustic excitation and the oscillating bubble-induced synthetic jet are experimentally investigated by high-speed images and μPIV (microParticle Image Velocimetry), respectively. Second, the rotating speed of a miniature rotor actuated by the oscillating bubbles-induced synthetic jets is measured in different frequencies and distances from a piezoactuator which is the acoustic energy source. Third, the proposed energy harvesting technology is tested using a custom-made piezocantilever. The electric voltage generated from the vibrating piezocantilever is measured in different frequencies and times. Fourth, a custom-made electrical circuit is used to rectify the electric voltage generated from the vibrating piezocantilever. The output voltage and power generated from the piezocantilever are measured using the electrical circuit with different electric loads. The maximum power for the load (10 Ω) was measured to be about 165 μW. As proof of concept, storage capacitor charging tests are performed for the 0.1 μF and 1 μF capacitors. The maximum charged voltages on the 0.1 and 1 μF capacitors are 162 and 197 mV, respectively. Finally, in order to demonstrate the possibility of improving the electric energy density provided by the proposed energy harvesting technology, the effect of multiple piezocantilevers on the electric energy density is studied. The sum of the generated voltages from two piezocantilevers is almost doubled as compared with a single piezocantilever. The presented work would be helpful for the basic design of possible engineering applications to generate electrical power and to detect acoustic waves via generated electrical signals.

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