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# Energy harvesting based on acoustically oscillating liquid droplets

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ABSTRACT

This paper presents a novel actuator for harvesting energy from ambient acoustic noise using acoustically oscillating droplets. When a liquid droplet sitting on a piezocantilever is excited by an acoustic wave around its natural frequency, its oscillation simultaneously bends the piezocantilever, which generates electric power owing to the piezoelectric effect. The oscillation amplitudes of water droplets with three different sizes (2, 4, and 6 μl) hanging from a solid substrate were first investigated using high-speed images. The results showed that the droplet oscillation amplitude was strongly dependent on the applied frequency and was proportional to the droplet size. The maximum droplet oscillation amplitude occurred at the natural frequency of the droplets. Energy harvesting based on acoustically oscillating droplets was separately tested using a commercial piezocantilever. The oscillation behaviors of water droplets hanging from a flexible piezocantilever were also studied using high-speed images. The bending displacement and generated voltage of the piezocantilever by the acoustically oscillating water droplets were measured with a high-speed camera and digital oscilloscope, respectively, for different droplet sizes and distances between the droplet and piezoactuator. Both the bending displacement and generated voltage were strongly affected by the applied frequency and proportional to the droplet size but were inversely proportional to the distance. The force generated from the acoustically oscillating droplets was measured by using a load cell. The maximum force generated from the acoustically oscillating droplet (4 μl) was about 123.9 μN at the maximum bending displacement (about 1.5 mm). The output voltage and power generated from the piezocantilever actuated by the acoustically oscillating droplets were measured with a custom-made electric circuit (mainly consisting of a voltage rectifier and load) for different droplet sizes. The maximum generated power for the load (10 Ω) was measured to be about 80 μW. As proof of concept, storage capacitor charging tests were conducted for 0.1 and 1 μF capacitors using the acoustically oscillating droplets in three different sizes.



## 1. Introduction

With the growing interest in portable wireless devices, the development of micro energy harvesting technology has become an important task [1–3]. Energy harvesting, which is also called power harvesting or energy scavenging, is defined as capturing energy from one or more surrounding energy sources, collecting it, and storing it for later use. Although portable wireless devices offer several advantages, such as flexibility and the ability to facilitate the placement of sensors in previously inaccessible locations, the use of batteries as the power source limits their potential because of the short battery life [2–6].

Hence, various micro energy harvesting technologies, mainly powered by four energy sources—light, radio-frequency electromagnetic radiation, thermal gradients, and mechanical motion—have been investigated and developed as potential alternatives to batteries [2,7]. Recently, Krupenkin and Taylor investigated a new type of high-power energy harvesting system based on the reverse electrowetting-on-dielectric principle that generates electrical energy through the interaction of arrays of moving tiny liquid droplets with a multilayer thin film [8]. They developed an in-shoe system that can harvest energy generated by walking and use it to recharge portable electronic devices later; their system received substantial attention from the mass media.

Among the various types of energy harvesting technologies, piezoelectric energy harvesting based on mechanical vibration is the most popular owing to its simple structure [9–12]. The piezoelectric effect converts mechanical strain into electric voltage and current. This paper presents a novel actuator for harvesting energy from ambient acoustic noise using acoustically oscillating droplets. When a liquid droplet attached to the tip of a piezocantilever is excited by an acoustic wave around its natural frequency, its

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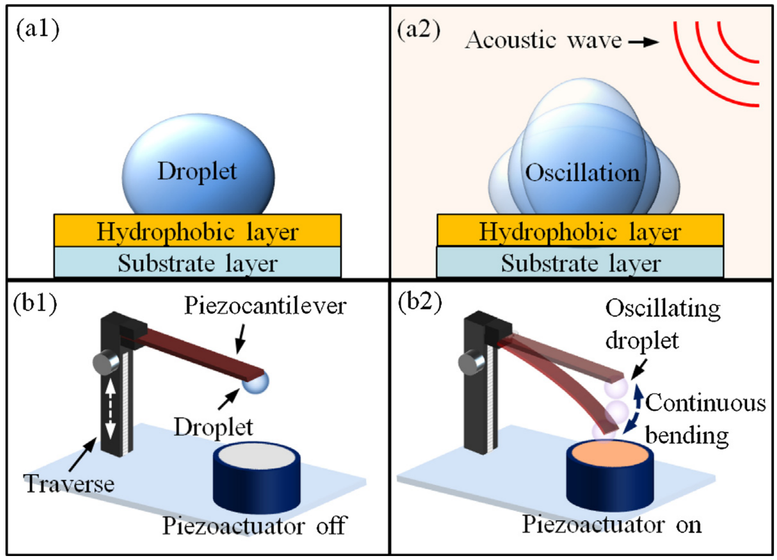


**Fig. 1.** Acoustically oscillating droplet-induced motion-powered energy harvester: (a) a water droplet oscillates when it is acoustically excited by a piezoactuator around its natural frequency. (b) when an acoustically oscillating droplet is placed at the end-tip of a piezocantilever, the oscillating motion of the droplet induces continuous bending of the piezocantilever as a reaction, which generates electric power.

oscillation simultaneously bends the piezocantilever, which generates electric power owing to the piezoelectric effect, as shown in Fig. 1 [13,14].

The envisioned energy harvesting system can extract mechanical power from acoustic noise over a wide range of frequencies using liquid droplets with different sizes and natural frequencies and convert the mechanical power to electrical power for wireless electronic devices. This new type of actuation technique is a simple but useful tool not only for energy harvesting systems but also for potential acoustic wave sensors and actuators in the future. Note that a preliminary report on this work was presented at the International Conference on Micro Electro Mechanical Systems held in San Francisco, USA [15].

## 2. Theoretical background

The behavior of a liquid droplet exposed to external disturbances is not only of scientific interest but is also an important research topic for various industrial applications such as power plants and heating, ventilation, and air-conditioning systems [16,17]. Liquid droplets generated from condensation processes attach to the surface of heat exchangers and reduce their efficiency because they provide thermal resistance. Hence, to efficiently remove liquid droplets from a surface, various methods such as surface treatments and vibration techniques have been developed along with the oscillation analysis of liquid droplets under external disturbances [17–20].

Rayleigh and Kelvin first studied the free oscillation behavior of spherical liquid droplets [21,22]. Later, Lamb extended the investigation to the oscillation behavior and frequency of a liquid sphere surrounded by an outer fluid with a different density [23,24]. Strani and Sabetta analyzed the oscillation of a liquid droplet in partial contact with a concave solid substrate by combining the Green function method with the Legendre series expansion [24]. Although their analysis was developed for a liquid droplet sitting on a concave solid substrate, it can be applied to predicting the oscillation behavior of a non-wetting droplet sitting on a plain solid substrate [25].

A pendant-shaped liquid droplet attached to the bottom tip of a piezocantilever is affected by gravity; however, it can adhere to the substrate owing to surface tension, as shown in Fig. 1(b). The force balance between gravity and surface tension is as follows [17]:

$$mg = \pi d\sigma \sin\theta \tag{1}$$

where $m$ is the mass of the liquid droplet, $g$ is the gravitational acceleration, $d$ is the diameter of the contact area, $\sigma$ is the surface tension, and $\theta$ is the contact angle.

When a liquid droplet is excited by an acoustic wave around its natural frequency, its oscillation motion simultaneously induces the bending of the piezocantilever to generate electric power. However, the oscillation motion of the liquid droplet is weak and negligible at different frequencies because it only responds around its natural frequency [26,27]. Hence, estimating the natural frequency is important to current energy harvesting systems. The most easily accessible theory for the natural frequency is for the oscillation of a free liquid droplet. The natural frequency of the $n$th mode oscillation of a free droplet is given by [17]

$$f_n = \frac{1}{2\pi}\left[n(n-1)(n+2)\frac{\sigma}{\rho R^3}\right]^{\frac{1}{2}}. \tag{2}$$

where $\sigma$ is the surface tension of the droplet, $\rho$ is the density of the droplet, $R$ is the radius of the droplet, and the mode number $n$ denotes the number of nodes occurring in the oscillation.

The oscillation of a water droplet (2, 4, and 6 μl) was observed with a high-speed camera (Phantom Miro eX4, Vision Research, Inc.). When a water droplet hanging from a solid substrate coated with a Teflon layer was acoustically excited by a cylindrical piezoactuator (PIC151, Physik Instrumente, Inc.) placed 4 mm away around its natural frequency, it continuously deformed (oscillated) with respect to the applied frequency, as shown in the inset of Fig. 2. This figure plots the oscillation amplitudes of the droplet actuated by acoustic waves generated from the piezoactuator in a wide range of frequencies as measured from high-speed images. The droplet oscillation amplitude was found to be strongly dependent on the applied frequency and proportional to the droplet size. The maximum droplet oscillation amplitude occurred at the droplet's natural frequency, which is a function of the droplet size [20,26,28]. The natural frequencies for the droplets (124, 96, and 63.3 Hz for 2, 4, and 6 μl, respectively) in the experiment deviated from the theoretical values (1.79%, 20%, and 27.6% for 2, 4, and 6 μl, respectively).