Energy Harvesting through Droplet-Induced Vibrations on Circular Membranes

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ABSTRACT

This study explores energy harvesting through droplet impact on flexible circular membranes, a relatively uncharted area. By analyzing droplet behavior and comparing experimental results with theoretical models, we propose innovative energy harvesting methods using piezoelectric devices for membrane displacement and triboelectric devices for droplet spreading.

KEY WORDS

Circular membrane, Drop impact, Energy harvesting

1. INTRODUCTION

As an alternative solution to address environmental pollution and energy scarcity, eco-friendly energy technologies are receiving increasing attention. Among these, energy harvesting technology gathers energy from natural sources and converts it into electrical energy, making it particularly useful for low-power devices.

This study aims to conduct foundational research to develop a device that harvests energy by converting the mechanical energy of raindrop impacts into electricity using piezoelectric materials. Piezoelectric and triboelectric materials generate current when subjected to vibration, pressure, or friction, as the internal dipole moments shift in response to these forces. The current generated is proportional to the material's dipole moments and the frequency of moment changes. [1] Thus, thin film structures with high frequencies and large deformation are advantageous in this process.

Previous research has focused on piezoelectric devices using cantilevered or fixed flexible surfaces [2,3] and triboelectric devices using liquid-solid contact on rigid surfaces. [4,5] However, studies on circular elastic membrane structures remain limited. This research aims to visualize and analyze the interactions between droplets and a circular membrane using a trampoline structure, quantify the energy obtained, and ultimately develop an energy harvesting device that utilizes raindrops.

2. EXPERIMENTS AND RESULTS

2.1 Experiment methods

To analyze the impact behavior between droplets and the circular membrane, we set up an experimental apparatus as shown in Figure 1. Droplets were released onto a circular membrane fixed in a trampoline-like structure, falling under their own weight. Camera 1 was used to visualize the spreading radius of the droplet, while Camera 2 captured the vertical displacement of the lower part of the circular membrane. The experimental variables, as listed in Table 1, included droplet impact velocity, membrane diameter, thickness, and material. The experiments were conducted by varying these parameters.

Table 1: Experimental parameter\

Variable	Value
Impact velocity	0.98~1.98 m/s
Droplet diameter	2~2.5 mm
Membrane diameter	30~700 mm
Membrane thickness	80~500 um
Substrate type	PDMS, Ecoflex, Latex

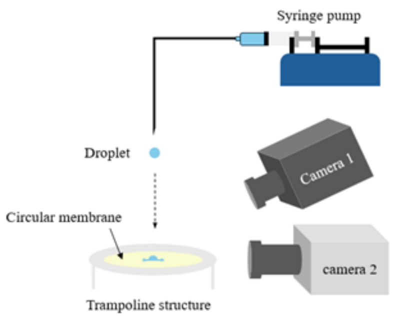

Fig.1: Schematic of experimental setup

2.2 Experimental results

First, as shown in Figure 2, an experiment was conducted to observe the spreading radius (R_s) of the droplet and the vertical displacement (δ) of the membrane surface depending on membrane thickness. When the thickness was infinitely increased, it was considered a rigid surface. Comparing this to a typical flexible surface, it was observed that R_s was smaller on the flexible surface due to the vertical displacement of the

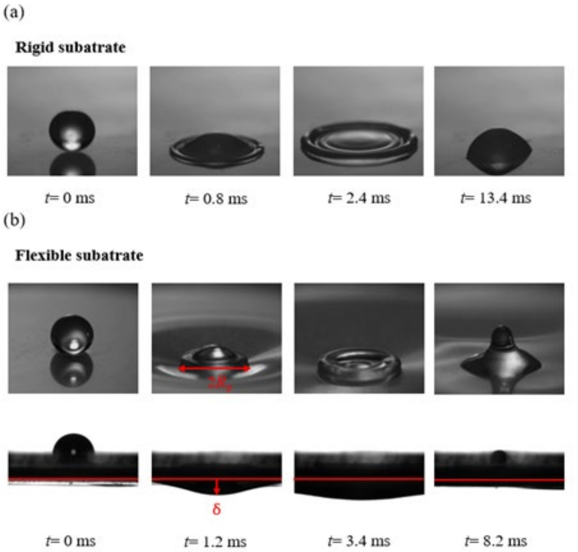

Fig.2: Sequential illustration of the collision of a water droplet onto (a) a rigid and (b) a flexible surface.

membrane during droplet impact. Additionally, unlike typical membrane waves in a (0,1) mode, the circular membrane displayed a complex vibration pattern influenced by the droplet's oscillations and energy dissipation on the surface, resulting in multiple overlapping vibration modes.

Next, the characteristics were examined according to droplet impact velocity. Droplets were impacted at speeds of 0.99 m/s and 1.4 m/s, and R_s and δ were analyzed at each speed. It was observed that the maximum spreading radius ($R_{s,max}$) increased as the impact velocity (v) increased. Defining the droplet's kinetic energy as KE and surface energy as SE, the kinetic energy and surface energy before impact were given by $KE_1= (1/2)(\rho v^2)(\pi/6)(D_0^3)$ and $SE_1=\pi D_0^2\gamma$, respectively. After the impact, at the maximum spreading radius $R_{s,max}$, the kinetic energy $KE_2=0$, and the surface energy $SE_2=\pi/4\ D_{max}^2\gamma(1-\cos\theta_a)$.[6] Thus, as v increased, the increase in post-impact surface energy led to an increase in $D_{max} =2R_{s,max}$

Additionally, Figure 3(a) shows that as v increased, the membrane's maximum vertical displacement (δ_{max}) increased, and the vibration period (τ) decreased. The maximum impact force exerted by the droplet during collision, $F\sim (1/2)m_{drop}v^2\pi R_{drop}^2$, was observed to be proportional to δ and the vibration frequency f, where the frequency f=1/τ, making it inversely proportional to the period. Consequently, the relationship between δ_{max} and τ according to v aligns with these findings.

Using these results, a basic energy harvesting device was constructed with a piezoelectric sensor. Like previous experiments, a piezoelectric sensor with a circular membrane structure was attached to a trampoline-like setup, and the voltage generated upon droplet impact was measured. As shown in Figure 3(b), the time-dependent voltage variation with different droplet impact speeds showed a similar trend to Figure 3(c), where δ_{max} increased and τ decreased as v increased.

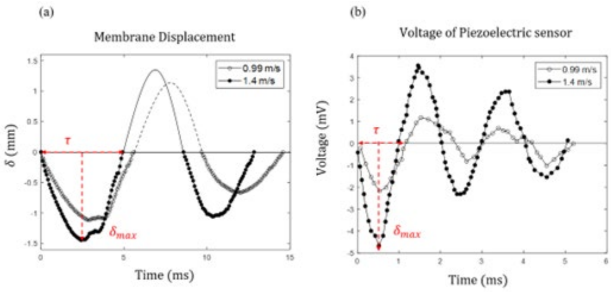

Fig.3: Images of (a) vertical displacement of the membrane, and (b) voltage generated by the piezoelectric sensor at different droplet impact velocities

3. CONCLUSION

This study visualized and analyzed the impact process between a circular membrane and a droplet, revealing the specific vibration characteristics involved. Based on these results, we developed a piezoelectric device utilizing membrane deformation and a triboelectric device based on the droplet spreading radius. The voltage generated by each device was measured, confirming consistency with the trends observed in previous experiments. Therefore, applying the findings of this study is expected to contribute to the advancement of novel, hybrid energy harvesting technology using raindrops.

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