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Flexible piezoelectric liquid volume sensor

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ABSTRACT

We report a non-contact type polyvinylidene fluoride (PVDF)-based liquid volume sensor. When a liquid container vibrates due to an applied impact, our sensor that is attached to the wall of the container detects the resonance frequency of vibration, which shifts as a result of change in liquid volume. The sensitivity of our sensor was enhanced by stacking multiple sensors in series. A PVDF bimorph actuator was also fabricated to demonstrate an integrated actuator-sensor system. We believe that the results presented in this work will pave the way for novel applications in volume sensing.

1. Introduction

With emerging technologies such as internet of things (IoT), the demand for various types of sensors is expected to grow in the near future [1–3]. High sensitivity, simplicity, low-cost, and in some cases, light-weight and flexibility are critical features that determine the feasibility of a sensor for a given application. Among various sensors required for IoT, mechanical sensors operating in response to pressure, vibration, strain are needed for a wide variety of applications such as wearable devices, smart home systems, and industrial equipment monitoring.

Piezoelectric materials can convert various mechanical stimuli such as vibration [4,5], pressure [6,7], sound [8,9], ultrasonic wave [10], wind [11] and human activity [12] into electrical signal; therefore, they are highly feasible materials for various mechanical sensing applications. Polyvinylidene fluoride (PVDF) and its copolymers are particularly promising due to a number of advantages such as high sensitivity (high piezoelectric stress constant), low-cost processability, mechanical robustness, flexibility, chemical stability, and a broad frequency range. Moreover, the devices integrated with flexible piezoelectric polymers can be easily attached to or embedded in various objects and human body. For example, the road-tire friction sensor composed of cantilever beam and PVDF film was attached to the inner surface of a tire by Erdogan et al. [13]. Lee et al. placed micro-patterned polyvinylidene fluoride-co-trifluoroethylene nanogenerator as self-powered pressure sensor on windows [14] and Park et al. placed piezoelectric polymer sensors on wrist and throat for health monitoring [15].

Liquid volume sensors (also known as liquid level sensors) have been gaining interest in recent years for applications such as healthcare, flood level monitoring, fuel storage system, and chemical processing [16–18]. Various methods such as mechanical [19], acoustic [20], electromagnetic [21], ultrasonic [22], capacitive [23] and optical [24–28] have been employed to measure the liquid volume change. Most of these methods, however, measure volume with the sensor in direct contact with the liquid, which can often contaminate the liquid and damage the sensor.

To overcome the aforementioned limitations, several different non-contact liquid volume sensing approaches have been developed. Bera et al. used a capacitance-type transducer for measuring the volume of conductive liquid, where the liquid was used as one of the electrodes [29]. Their device showed high degree of repeatability; however, the sensor needs to be similar in height as that of the container, requiring the change in sensor design with different containers. Tatsuo et al. utilized a millimeter-wave Doppler sensor for detecting liquid level on the basis of absorption of millimeter waves in liquid [30,31]. This technique enables accurate volume measurement of different liquids; however, it requires a

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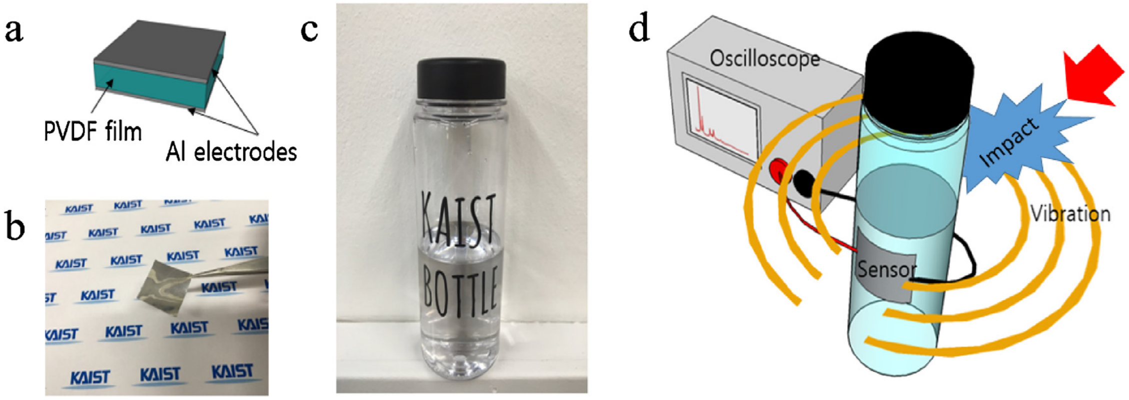

Fig. 1. (a) Schematic and (b) photograph of flexible PVDF film-based piezoelectric volume sensor. (c) A photograph of a plastic liquid container, used for this study. (d) Illustration of the experimental setup for measuring liquid volume.

vertical linear stage. Luckum and Jakoby used an electromagnetic-acoustic resonator sensor to measure the change in liquid volume on the order of several microliters, but this sensor is not suitable for detecting large volume changes [18]. In general, these approaches are limited in their possible applications due to their complexity and the size of the measurement apparatus.

In this article, we demonstrate a PVDF-based flexible non-contact liquid volume sensor. Our device is simple, low-cost, and can be easily be applied to containers of various sizes and shapes. Our device is attached to the surface of a container and the volume is detected by measuring the resonance frequency of the container. To increase the sensitivity of our sensor, multiple devices were stacked in series. Finally, we fabricated a PVDF-based actuator to demonstrate an integrated actuator-sensor system. Our sensor has a wide variety of applications where monitoring of liquid volume or density in a simple non-contact manner is required. It can be used in homes to detect the volume of various food items remotely or to detect the content of liquid products (e.g. solute concentration) in industry without having to open the package.

2. Materials and methods

PVDF films were purchased from Measurement Specialties, Inc. 20 nm of Al electrodes were thermally evaporated onto both sides of the PVDF films by a vacuum thermal evaporation. The deposition was conducted under a pressure of 10^{-6} Torr. For the pendulum, the mass of the bob was 6.36 g, and the length of the thread was 15 cm. The applied force was varied by adjusting the height at which the bob was dropped, and the force was measured using a force gauge (M5-2, Mark-10). Input resistance and capacitance at the probe tip of the oscilloscope were 10 MΩ and < 8 pF, respectively. All measurements were conducted at 25 ± 1 °C. In order to measure the performance of a PVDF actuator, the input voltage was supplied with a function generator

(8023, Tabor Electronics Ltd) connected to a voltage amplifier (F20A, FLC Electronics). The displacement of the actuator was measured with a laser displacement sensor (OD85-20T1, Sensick), and the impact force generated by the free end of the actuator was measured by a load cell (GSO-30, Transducer Techniques).

3. Results and discussion

PVDF device was fabricated by evaporating Al metal on the top and bottom surface of a 50 μm thick PVDF film of 2 × 2 cm^2 in area, as depicted in Fig. 1a. A photograph of the PVDF device and the plastic (polyethylene terephthalate) liquid container used for our experiments are shown in Fig. 1b and c, respectively. The shape of the liquid container was a cylinder with a height and radius of 19.1 cm and 3.2 cm, respectively. The wall thickness was 1.4 mm and the maximum volume was 500 ml. Distilled water was used as our liquid. Controlled amount of force was applied to the liquid container using a pendulum. The electrical output signal from the PVDF device was measured using an oscilloscope (Tektronix DPO 3034) as seen in Fig. 1d.

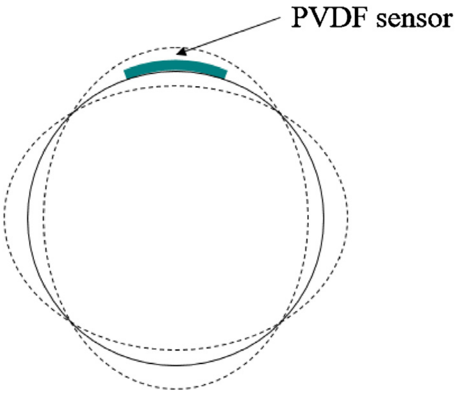

Fig. 2. Schematic of a liquid container vibrating in (1,2) mode, and a PVDF sensor attached to the surface of the container.

Due to the small thickness of the film along with its flexibility, our PVDF volume sensor was easily attachable to the surface of the liquid container. When vibration was induced on the liquid container by an external force, the vibration was transduced into voltage signal by the PVDF, which was then measured using an oscilloscope. The vibration modes of a liquid container are similar to the flexural modes of a bell and a wineglass, and they result from the propagation of bending waves around the liquid container [32,33]. The fundamental mode of the liquid container is the (1,2) mode ($m = 1, n = 2$), whose axial half wave number is 1 and circumferential wave number is 2. In this mode, the wall of the container changes from circular to elliptical twice per cycle (Fig. 2) [32,33]. The movement consists of radial and tangential motions, and each motion is proportional to $n \sin(n\theta)$ and $\cos(n\theta)$, respectively [34]. Therefore, the PVDF sensor attached to the container receives repeated normal and tangential stress during vibration, and converts the mechanical energy into electricity *via* piezoelectric effect.

As the volume of water increased from 0 to 500 ml, the peak-to-peak output voltage decreased from 22.8 V to 12 V for a force of 11.3 N (Fig. 3a–c). On the other hand, the duration of the output signal increased as the volume of water increased. The vibration of the liquid container with sensor attached can be considered as a free damped vibration because force was only applied once initially