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Ferrofluid-based triboelectric-electromagnetic hybrid generator for sensitive and sustainable vibration energy harvesting

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ABSTRACT

A vibration energy harvester that utilizes a liquid medium has been the subject of active research recently given its advantages of shape adaptability, scalability, and durability. In this work, a ferrofluid-based vibration energy harvester with a hybrid triboelectric-electromagnetic operating mechanism is proposed for the first time. The ferrofluid suspension solution is made with water and magnetic nanoparticles. Electrostatic induction between the polymer sidewall and the solvent water activates a triboelectric generator component, while electromagnetic induction between the suspended magnetic nanoparticles and an outer coil activates the electromagnetic generator component. Experimental results for the ferrofluid-embedded hybrid energy harvester showed an extremely low threshold amplitude and a wide operating frequency range, both of which can be particularly advantageous for harvesting subtle and irregular vibrations.

1. Introduction

The triboelectric nanogenerator (TENG) is a new class of vibration energy harvester based on contact electrification [1] and electrostatic induction processes. It has attracted considerable interest due to its high power and simple device structure, and utilizes low-cost materials [2–21]. Various TENG designs have been developed for scavenging ambient and environmental vibration energy from sources including human motion [22,23], acoustic sound [24,25] and water waves [26]. In order to further increase efficiency, hybrid energy harvesters, which simultaneously utilize two energy harvesting mechanisms in a single body, have been actively investigated recently. In particular, a hybrid device combining a TENG and an electromagnetic generator (EMG) has shown potential as a practical and highly efficient mechanical energy harvester [27–29].

Although the energy output efficiency of the TENG has been rapidly improving, issues with endurance against abrasion still need to be addressed, because the contact electrification process involves physical rubbing or collisions. In this regard, a couple of works have reported that liquid-solid contact electrification can work as well as the conventional solid-solid contact electrification [30,31]. Because contact between a liquid and a solid surface produces much less physical stress, the undesirable but unavoidable friction of solid-solid contact electrification can be naturally mitigated.

Herein, we introduce a ferrofluid-based vibration energy harvester based on the triboelectric-electromagnetic hybrid mechanism. Ferrofluids are colloidal liquids incorporating magnetic nanoparticles, which are dispersed in an organic solvent or water. The magnetic nanoparticles can be magnetized under an external magnetic field, while the liquid properties are unaffected. Since their initial development [32], ferrofluids have been widely applied, including for electronic devices [33], as mechanical lubricants [34], in medical applications [35], optics [36] and electromagnetic generators [37–40].

In the proposed ferrofluid-based triboelectric-electromagnetic (FF-TEEM) generator, the TENG and the EMG components are packaged into a single-body structure, and when the ferrofluid is agitated by an external mechanical excitation, it simultaneously activates both generators. The electrostatic properties of the water solvent, and the magnetic properties of the suspended particles, are thus independently used for the TENG and the EMG components, respectively. The hybrid design offers a complementary synergy in output performance as well as the practical benefit of mass-normalized output energy [41] with mechanical endurance. In addition, the packaged structure guarantees high immunity against environmental effects such as humidity and airborne debris [42].

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2. Experimental section

A. Ferrofluid preparation

The ferrofluid (EMG 707) in this study was supplied by Ferrotec Korea Co., Ltd. EMG 707 is a water-based ferrofluid containing suspended iron oxide (a mixture of Fe3O4 and Fe2O3) nanoparticles coated with an anionic surfactant. The density of this ferrofluid ranges from 1.05 to 1.15 g/cm3 at room temperature. The average diameter of the nanoparticles is about 10 nm. The iron oxide nanoparticles have superparamagnetic properties, and the saturation magnetization of the ferrofluid ranges from 9 mT to 11 mT.

B. Measurement apparatus

The experimental system was composed of a function generator (33, 120 hp), a power amplifier (PA-141, Labworks Inc.) and an electro-dynamic shaker (LW140.141–110, Labworks Inc.). First, the function generator (33, 120 hp) provides a sine wave signal to the power amplifier (PA-141, Labworks Inc.) with controllable amplitude and frequency levels. The electrodynamic shaker converts the amplified electrical signal into actual mechanical vibration, which is delivered to the FF-TEEM generator. The output signal generated by the FF-TEEM generator is then measured by an electrometer (Keithley 6514).

3. Results and discussion

The proposed ferrofluid-based triboelectric-electromagnetic (FF-TEEM) generator is composed of a hollow cylindrical tube, half filled with a ferrofluid (Fig. 1). The inner sidewall is made of polytetrafluoroethylene (PTFE), which has the most negative order of electrification [43]. The outer sidewall is surrounded by two separate top and bottom electrodes which consist of Al. A wire coil is wound around the outer wall for 200 turns. A 2230 Gauss permanent magnet (NdFeB) is positioned at the bottom end of the device to polarize the magnetic nanoparticles inside the ferrofluid. No magnet is placed at the top end in order to concentrate all of the ferrofluid in the bottom half in a neutral state. The Al electrodes are in the shape of a ‘C’, that is, a cylindrical shape with a small gap, as shown in Fig. 1a. The shape of this design prevents eddy currents and the ensuing damping effect. The outer diameter is 30 mm, the inner diameter is 28 mm, and the outer height is 80 mm, while the inner height is 60 mm, the heights of the top and bottom electrodes are 29 mm in each case, the space between two electrodes is 2 mm, and the distance between the magnet and the bottom end of the ferrofluid is 5 mm. Finally, the total mass of the device is 41.4 g.

A ferrofluid sloshes under external vibration, and the sloshing ferrofluid induces two phenomena. The first phenomenon is the electrostatic screening by the water solvent toward the fixed triboelectric charges in the PTFE sidewall (Fig. 2a). After repeated contact with the ferrofluid, the PTFE contains strong and immobile negative triboelectric charges according to the different orders of electrification against water [44]. In a stable state, the negative triboelectric charges of the PTFE attract positive counter-charges in the outer Al electrode by Coulombic interaction. When the positive charges of the water solvent electrostatically screen the negative triboelectric charges of the PTFE, this triggers redistribution of the positive counter charges in the Al electrodes. The movements of the positive counter charges induce a charge density imbalance across the two electrodes, which results in the generation of current. As the vibration continues, a continuous alternating current (AC) is generated between the two electrodes.

The other electricity generation mechanism in the FF-TEEM generator is a change in electromagnetic flux (Fig. 2b). In stable conditions, the magnetic nanoparticles maintain a fixed state of polarization, and behave like a bulk magnet. Therefore, any change in the shape of the ferrofluid induces a time-varying magnetic flux. The time-varying magnetic flux generates current in the outer coil according to Lenz's law.

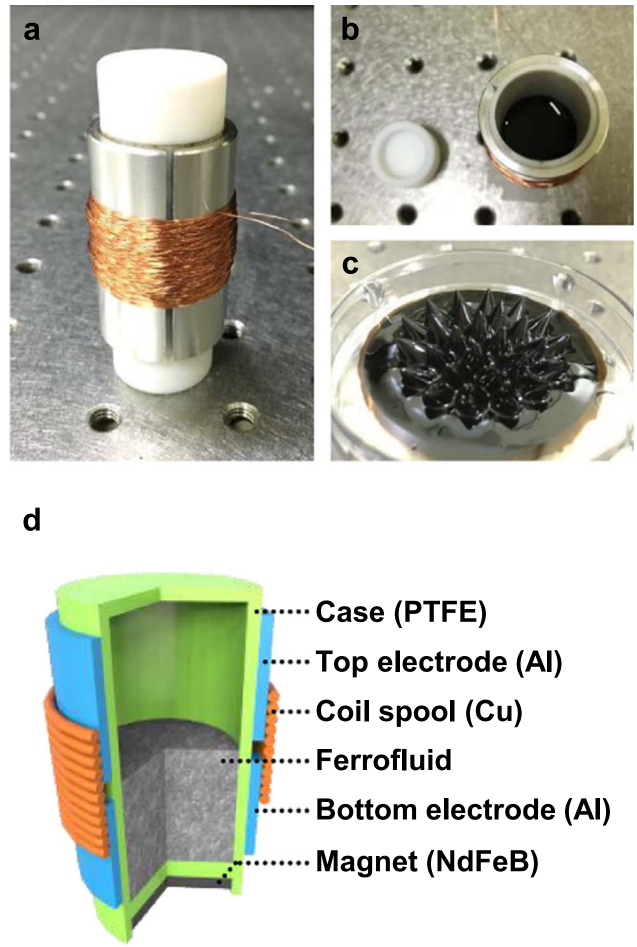

Fig. 1. Structure of the FF-TEEM generator: (a) An image of the outer body. (b) An image of inner body when the upper cover is open. (c) Ferrofluid pattern when the permanent magnet is positioned in the lower section. A stronger magnet was used to create this image. There is no clear ferrofluid pattern in the actual experimental device because it uses a lower intensity magnet.

In these ways, the energy of the external vibrational simultaneously operates an electromagnetic generator (EMG) and a triboelectric nanogenerator (TENG).

The measurement apparatus for the study is explained in the experimental section. A consistent vibration with sinusoidal movement was applied to the FF-TEEM generator, and the output open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}) were measured. The vibration amplitude and frequency were 9 mm and 7 Hz, respectively, which produced a stable sloshing motion in the ferrofluid medium. The voltage and current between the top and the bottom electrodes of the TENG component were measured, and the voltage and current between the two coil ends were simultaneously measured for the EMG component.

Given the mechanisms described above, regular output signals with a sinusoidal shape were observed (Fig. 3). The frequencies of the output signals were synchronized, and closely followed that of the input vibration. The TENG component presented a peak-to-peak V_{oc} value of 0.23 V and an instantaneous I_{sc} value of 2.7 nA. The EMG component showed a peak-to-peak V_{oc} of 1.8 mV and an instantaneous I_{sc} of 2.5 μA.

As noted in previous studies, the TENG provides high voltage and low current while the EMG provides low voltage and high current. This difference stems from the different output resistance levels of the components [45]. The internal resistance of the TENG component is large, and the output voltage is determined by the charging of parasitic capacitance instead of by Ohmic current [46]. In contrast, the internal