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Triboelectric Power Generation from Paper Vibration Induced by Sonic Waves

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Abstract: Paper is a material with a high Young's modulus that vibrates sensitively due to environmental noise, voice, and sound. This study aims to create a triboelectric power generator to convert this sonic vibration energy into electrical energy to power microelectronics embedded on paper. A sonic wave has two wave modes, transverse and longitudinal, that propagate in paper; therefore, two types of triboelectric power generators were designed for trial simulation as the first step. A triboelectrically charged polytetrafluoroethylene sheet and a back electrode were attached to a paperboard. Another paperboard with a counter electrode attached was vibrated in the out-of-plane direction corresponding to transverse waves such that it would repeatedly move toward and away from the other paperboard. The generated power between the two electrodes reached 11.8 μW at 2 MΩ load. When comb-shaped electrodes were applied, manual strokes in the in-plane direction, corresponding to a longitudinal wave, induced voltage up to 8.2 V. The result suggested that sonic waves could be an electric power source for microelectronics in the future.

Keywords: electret, fast Fourier transform, paper, resonance frequency, vibration energy

Introduction

Information and communication technology devices such as smartphones, wearable electronics, and wireless sensors are being developed to implement new societies in which the Internet of Things and the Internet of Everything are ubiquitous. Such devices and tools always or frequently demand access to the Internet and therefore require sources of electric power. In place of conventional power sources such as dry batteries that must be frequently replaced and disposed. Energy harvesting, also referred to as energy scavenging, has opened up possibilities for a large variety of sources and conversion methods. The sources for energy harvesting are ambient and not autonomous, for example, light (direct sunlight, ambient light, and artificial light), heat (temperature variation and thermoelectricity), vibration (mechanical and electrostrictive) (Meddad et al. 2012), waves (acoustic noise and ambient radio frequency), piezoelectricity (Gullapalli et al. 2010), static electricity, and human life (walking, body heat, and blood flow) (Bhatnagar and Owende 2015). This study is focused on electrostatic induction using paper vibration caused by environmental noise, voice, and sound as an energy source.

The power generation mechanisms for transduction from vibration are, as discussed in (Beeby, Tudor, and White 2006), based on fundamentally inertial-based spring-mass systems with a damper for obtaining resonance movements. From energy conversion mechanisms such as piezoelectric, electromagnetic, and electrostatic systems, we chose an electrostatic system to achieve low weight. As for electrostatic systems, Sakane, Suzuki, and Kasagi (2008), Suzuki (2011), and Yang, Wang, and Zhang (2012) developed a micro electret generator with a 15-μm film of specialized perfluoropolymer with a charge density of 1.37 mC/m^2 that is higher than that of polytetrafluoroethylene (PTFE). An electret is a dielectric material with permanent electric charge. Naruse et al. (2008) has developed a horizontal type of vibration using a micro power generator consisting of microball bearings in which microballs roll with a constant separation gap. Comb-shaped electrodes were designed, and SiO_2 was applied as a proof mass. Low-frequency vibrations less than 10 Hz generated output power up to approximately 100 mW. Takahashi et al. (2012) introduced a vertical type of counter electrode coated with a ferroelectric material. This counter electrode can generate increasing output power with increasing capacitance without a comb-shaped electrode pattern. These power generators used an electret with the corona-charging method to inject charge. Other possible methods of charge injection include triboelectrification and electrostatic spinning (Tsai, Schreuder-Gibson, Gibson 2002). However, we chose triboelectrification to charge PTFE films because one sheet of paper with an electrode repeats to hit the

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other sheet of paper with an electret during vibration and induce triboelectrification. A flexible triboelectric generator (TriboEG) with polyimide (Kapton) and polyethylene terephthalate films was proposed by Fan, Tian, and Wang (2012). Spiral electrode based TriboEG with a bicylindrical structure was designed for harvesting energy of both rotational and translational motions (Guo et al. 2015). TriboEG was also applied to a self-powered vibration frequency sensor for machines operation monitoring (Liang et al. 2015). Harvesting energy from wind using triboelectric mechanisms was already confirmed with a system in which flexible gold-coated fabrics fluttered against a rigid gold-coated counter plate as a counter electrode with a PTFE film, giving an average power density of approximately 0.86 mW (Bae et al. 2014). Paper is also applicable to the system for transmission of mechanical movement to an electret. The origami structure works like a spring to transmit energy of stretching, lifting, and twisting motions (Yang et al. 2015).

The current study reports the trial simulation data for future application of paper vibration due to environmental noise, voice, and sound as an energy source instead of wind or mechanical motions, with voltage obtained from a prototype paperboard TriboEG. In this system, the weight and elasticity of paper in itself function as a proof mass and spring, respectively. During vibration, the paper keeps energy and it immediately transfers to electricity via electrostatic induction.

There are two directions in which a medium such as paper vibrates when a sonic wave travels through it. The two modes of waves are called longitudinal and transverse and consist of the oscillations occurring parallel and perpendicular to the direction of the propagation, respectively. The ratio of the two waves is related to the moduli of elasticity and rigidity. Two types of TriboEG were fabricated corresponding to the two waves such that the relative motion of an electret to the counter electrode was out-of-plane and in-plane. In this article, to simulate sound-induced power generation, a mechanical vibrator and paperboard were applied in a model experiment to amplify the electrostatically-induced power prior to the development of a practical generator with thin paper.

Experimental

Materials

Paperboard was applied as both a sound propagation material and a substrate to support an electret and electrodes. PTFE (Teflon, Du Pont, USA) and copper tape with electroconductive acrylate adhesive (CCH, Chomerics, USA) were applied as an electret and electrodes, respectively. Table 1 shows the physical properties of the materials used for fabricating the paperboard TriboEG.

Table 1: Condition of the paperboard TriboEG (out-of-plane motion).

Material	Property	Value
Paperboard	Grammage (g/m^2)	736
	Thickness (mm)	1.13
	Dimension (mm × mm)	90 × 209 (Fixed part) 90 × 153 (Moving part)
	Gap between fixed and moving parts (mm)	1 and 2
PTFE (Electret)	Thickness (mm)	0.50
	Dimension (mm × mm)	40 × 40
Copper (Electrode)	Thickness (mm)	0.036 (copper) 0.038 (conductive adhesive)
	Dimension (mm × mm)	25 × 125

Fabrication of the Paperboard TriboEG (Out-of-Plane Motion)

Figure 1 shows the design configuration of the paperboard TriboEG with an out-of-plane motion (Tao et al. 2015). Both the fixed and moving parts of the two paperboards were mounted on a stand such that the periphery would not be shifted and the narrow gap between the two paperboards would be maintained. To design the paperboard TriboEG, the condenser microphone structure (Sessler et al. 1962) was introduced. The vertical arrangement of this structure, which is popular for microphone applications, was equipped with a membrane functioning as a diaphragm to transfer sound-induced vibration into an electric signal via dielectric polarization. One of the advantages of this structure is its high flexibility and its applicability to paper and PTFE sheets. Paper is neutral

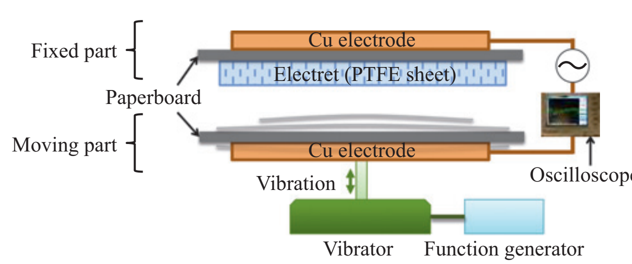

Figure 1: Design configuration of the paperboard TriboEG (out-of-plane motion).

in terms of electric charge. A PTFE sheet functions as an electret because it is a dielectric material with a permanent negative electric field created by corona discharge or simply rubbing it with another triboelectric material. Electrets have often been used effectively in conjunction with micromachining technology for electrostatic self-powered devices.

Fabrication of the Paperboard TriboEG (In-Plane Motion)

The propagation of a longitudinal wave was considered, and a paperboard TriboEG with an in-plane motion mechanism was designed using comb-shaped electrodes as shown in Figure 2. Two stiff paperboards were employed to fix the whole structure. The moving part at the top of this figure moves horizontally on a pair of guide rails with bearings on both sides for smooth linear motion (not shown in the figure), keeping a constant distance from the fixed part at the bottom. In the experiment of power generation, the moving part was quickly moved back and forth twice by hand.

Data Acquisition of Voltage and Power Generated by the Paperboard TriboEG

To vibrate the moving part, a vibrator (U56001 Vibration generator, 3B Scientific Physics, Germany) with a signal source from a multifunction generator (WF1973, NF Corporation, Japan) was used for the TriboEG (out-of-plane motion). To record the generated voltage, an oscilloscope (DSO1052B, Agilent Technologies, USA) was used for both the out-of-plane and in-plane motion modes. The voltage generated by the forced vibration from the vibrator was recorded by the oscilloscope under the conditions shown in Table 2 and analyzed using the fast Fourier transform (FFT) to determine the natural frequency of the paperboard and separate the generated electricity

Table 2: Data acquisition system of generated voltage.

Instrument	Property	Value
Vibrator and multifunction generator	Frequency (Hz)	Background, 10, 20, 30, 40, 46, 50 and 55
	Amplitude*2 $V_{p\text{-}p}$ (V)	10
Oscilloscope	Voltage full scale (V)	± 2
	Sampling rate (Hz)	500
	Recording period (s)	1.024

from the electric noise sourced by the power outlet in the room. The FFT calculation was conducted by using the analysis function of a spreadsheet application (Excel 2010, Microsoft Corp., USA). As shown in the next chapter, each Fourier coefficient (amplitude) of the background wave was subtracted from those of the measured voltage waves at every frequency in the Fourier space.

For output power measurements, electrostatic charges were provided to electret sheets, initially. A high voltage Corona discharge treatment (GC50S, Green Techno, Inc, Japan) with a bias needle voltage of –50 kV was applied back and forth 30 mm away from the surface of a PTFE electret with an area of 23,000 mm^2 and a thickness of 0.5 mm before attaching it on the paperboard TriboEG. Lee et al. (2011) reported that the charge density of electrets did not improve significantly without a high bias needle voltage. The default voltage –50 kV of the corona discharge in this work was high enough. Thus, the discharge time was set to 2 min and the surface potential started to be measured 1 min after discharge with a surface potential meter (digital static meter KSD-2000, Kasuga Denki, Inc., Japan).

Subsequently, output power was measured with a power meter (PW3335, Hioki E.E. Corp., Japan) with load resistances varied from 10 kΩ to 10 MΩ at 39 Hz in forced vibration for suitable vibration stability and achievement of a maximum power, 20 Vp-p in vibrator driving voltage, and 40 μm in displacement from the fixed paperboard to moving paperboard of the TriboEG.

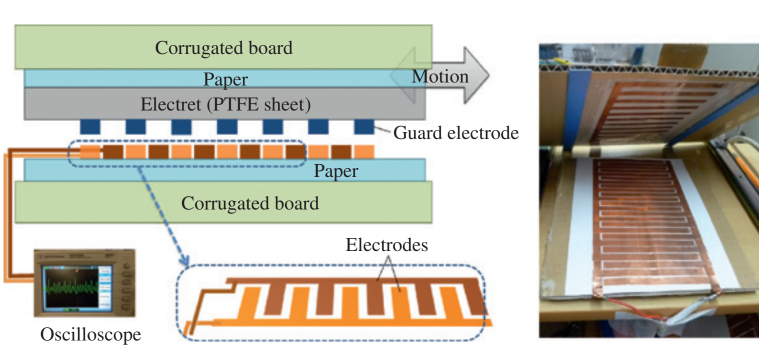

Figure 2: Design configuration of the paperboard TriboEG (in-plane motion) and photograph of apparatus.

Results and Discussion

Voltage and Power Generated by the Paperboard TriboEG (Out-of-Plane Motion)

Figure 3 shows the recorded voltage generated by the paperboard TEG due to out-of-plane motion at each frequency of forced vibration with a 2-mm gap between the two paperboards. The background noise consisted of a 51-Hz sinusoidal wave. (The specified frequency of a commercial power source in eastern Japan is 50 Hz). Therefore, all generated voltages include this background noise.

To distinguish the voltage generated by the vibrational motion, FFT was applied. The results of the FFT analysis of the voltages after normalization (background noise removal) are shown in Figure 4. Among the various forced frequencies, the highest amplitude of voltage, 2.3 V, was obtained at 46 Hz. This forced vibration is considered to provide resonance to the paperboard to meet the condition set in this configuration.

The gap between the fixed and moving parts should be as small as possible for effective energy generation by static electricity, because a maximum voltage is obtained at the maximum changing rate of the electric field. At a narrower gap of 1 mm, the paperboard TEG generated higher voltages as shown in Figure 5.

Figure 6 shows FFT spectra calculated from those generated voltages. The TriboEG system tended to be practically ineffective at forced vibration frequencies of 10 and 20 Hz; the highest peak voltage for both was only 0.1 V. From the 30 Hz forced vibration, the 1-mm gap configuration generated 1.1 V, which was more than

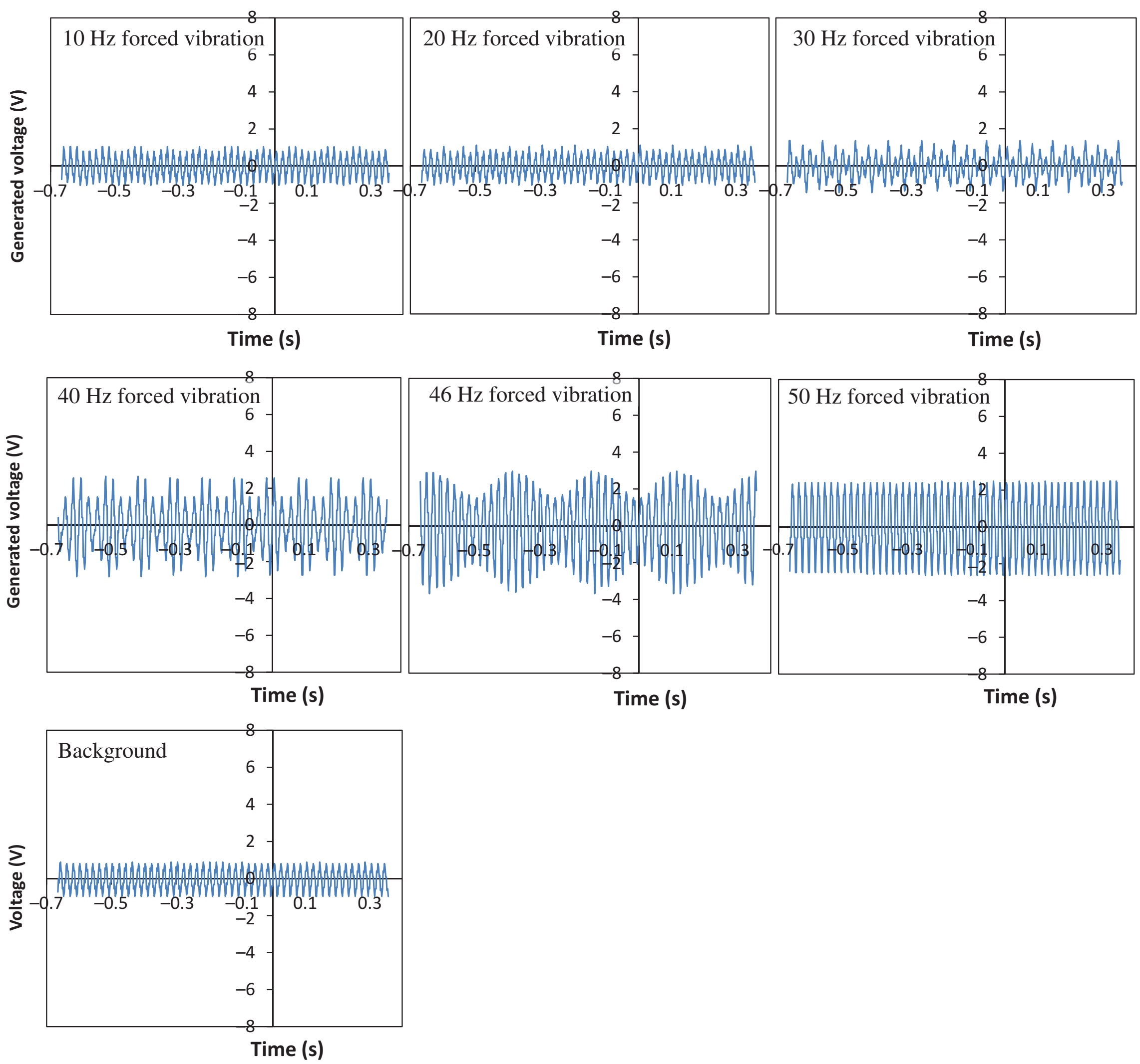

Figure 3: Voltages generated by paperboard TriboEG at a gap of 2 mm and voltage of background electric noise.

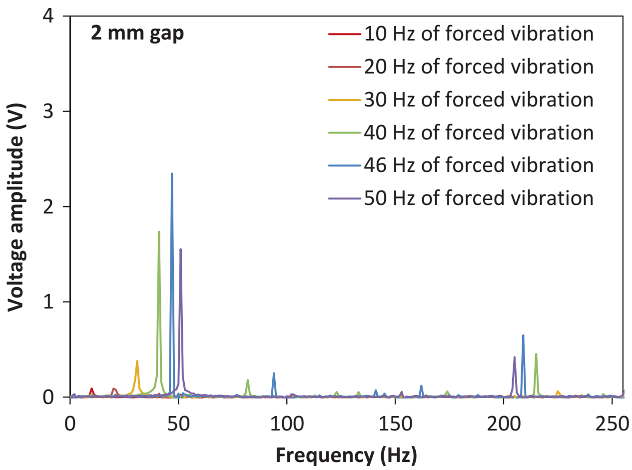

Figure 4: Spectra of voltage amplitude generated by paperboards at a gap of 2 mm with background noise subtracted.

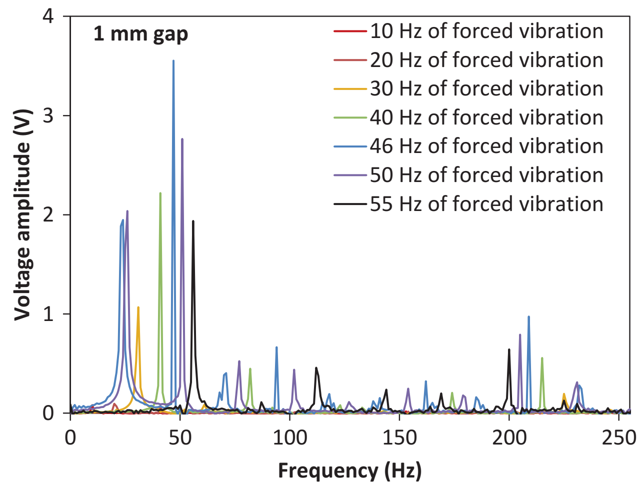

Figure 6: Voltages generated by paperboards at a gap of 1 mm with amplitude of background noise subtracted.

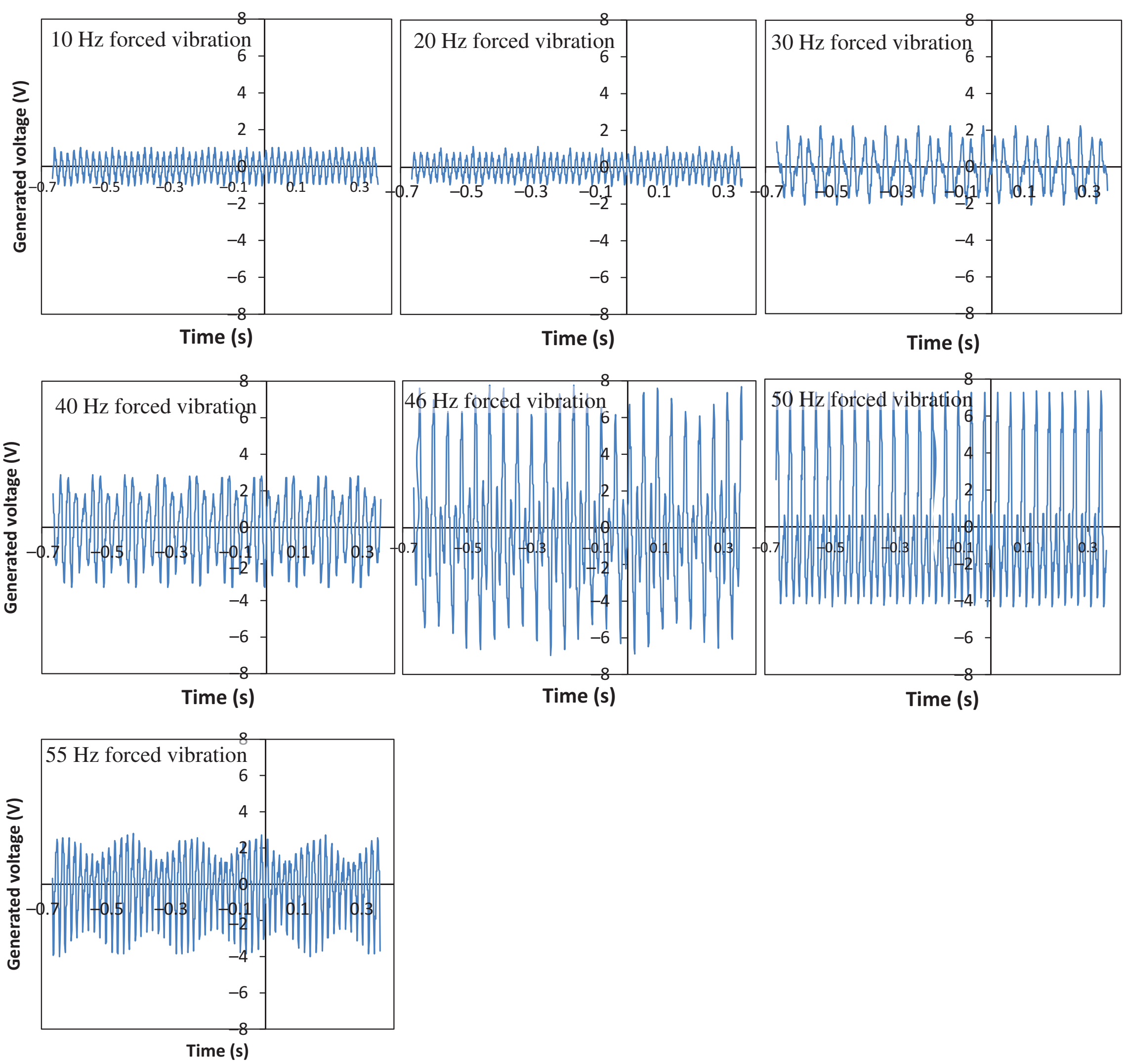

Figure 5: Voltages generated by paperboard triboelectric generator at a gap of 1 mm and voltage of background electric noise.

double that of the 2-mm gap (0.4 V). The TriboEG system achieved the highest peak voltage of 3.6 V at 47 Hz by a 46 Hz forced vibration. The peak voltage decreased for forced vibrations greater than 46 Hz to 2.8 and 1.9 V at 50 and 55 Hz, respectively. Large harmonic vibrations were observed at 24 and 26 Hz at forced vibrations of 46 and 50 Hz, respectively. The frequencies of those harmonic vibrations were located at approximately half the fundamental frequencies. It is unknown whether those harmonic vibrations may have contributed to power generation; however, in those few times, the higher frequencies were small and unlikely to contribute. Consequently, the maximum resonance seems to have appeared at a vibration frequency of approximately 46 Hz.

Figure 7 shows the measured output power with a maximum value of 11.8 μW at a load of 2 MΩ. Although the μW order power seems fairly large, it is high enough to light an LED. The maximum value is attained when the load resistance is equal to the internal resistance of the TriboEG circuit as is usually large.

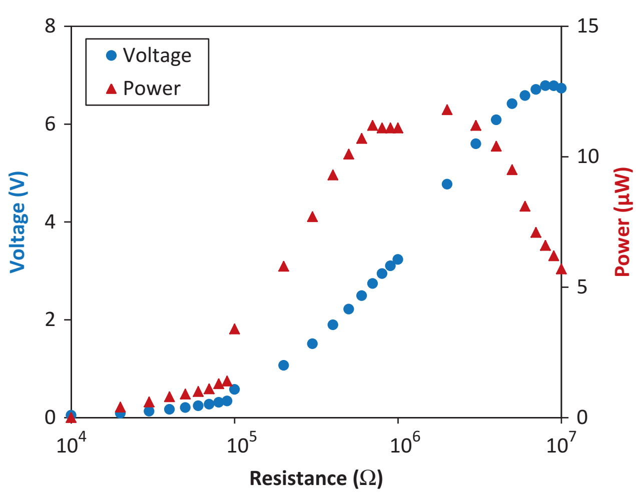

Figure 7: Output voltage and power profiles with load resistance.

Figure 8 shows surface potentials of PTFE sheets rubbed against copy paper for 1 min, corona-discharge-treated, and untreated for comparison. The surface potential of the untreated sheet was −0.09 kV. It was found that the rubbed PTFE sheet was provided with a high negative surface potential and kept it higher for about 10 min. Therefore, continuous rubbing action is required to keep the potential. Although the corona-discharge-treated PTFE sheet shows a rapid decrease in the negative potential for initial 30 min, it still kept a much higher negative charge than the rubbed PTFE sheet. Thus, corona-discharge-treated PTFE sheets can be applicable for active power generation. In electrochemical experiments,

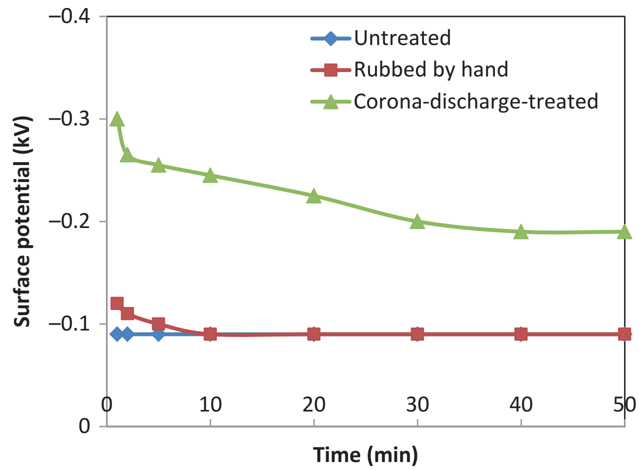

Figure 8: Surface potential changes of variously-treated PTFE sheets with time.

however, electrostatic charges on rubbed PTFE sheets were directly identified as electrons rather than ions (Liu et al. 2008). The realization of this prototype dielectric material is suitable for interactive power generation.

Voltage Generated by the Paperboard TriboEG (In-Plane Motion)

The paperboard TriboEG system for in-plane motion generated voltage with a sliding action by hand as shown in Figures 9 and 10 with a gap of 3 and 1 mm between the paperboards, respectively. In the generated voltage wave to the left of Figure 7, each of the four remarkable pulse waves were found to consist of 12 oscillations, corresponding to the number of teeth of the comb-shaped electrodes during the two round trips. The generated voltage wave to the left of Figure 8 shows a similar tendency except for a larger amplitude caused by the higher changing rate of the electric field induced by the narrower gap. The generated voltage momentarily reached 1.3 and 8.2 V at 3 and 1 mm gaps, respectively. The FFT amplitudes to the right of Figures 7 and 8 show the highest peaks at approximately 60–70 Hz. Those frequencies depended on the moving speed of the examiner's hand and the interval of the electrode teeth. Practical longitudinal waves of sound are weak, and their displacement is much smaller than that in this experiment. However, this result proved that in-plane displacement can generate electricity. This result further indicated that microscopic electrodes and electret printed two sheets of paper with smoothly finished surfaces at a high resolution could be an electric power source for microscopic electronics.

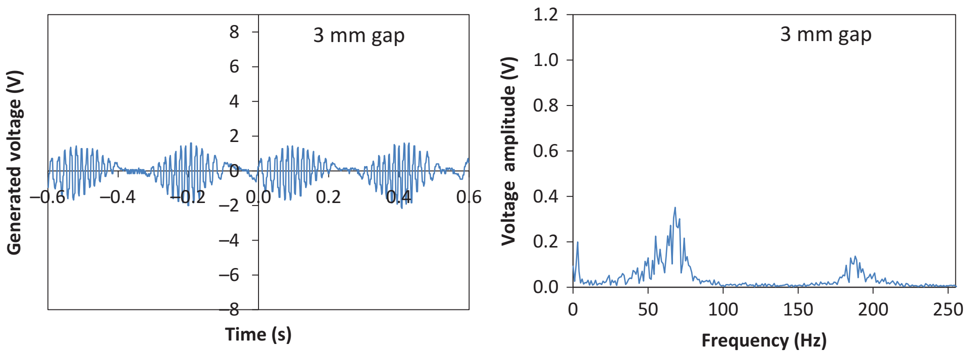

Figure 9: Voltage generated by paperboard TriboEG (in-plane mode) and voltage amplitude spectrum calculated by FFT at a gap of 3 mm.

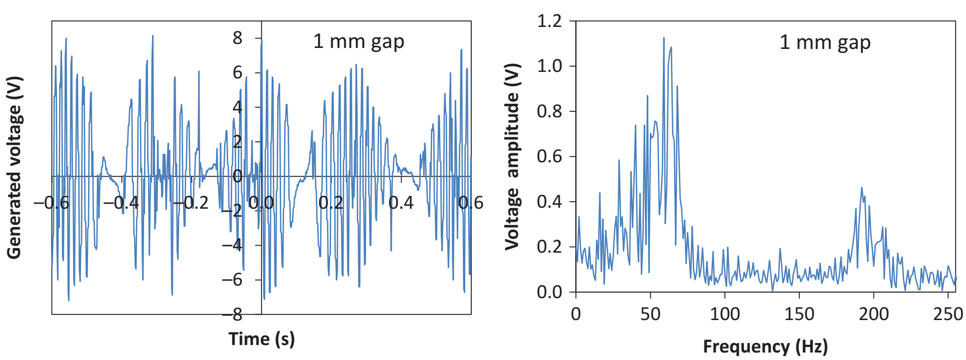

Figure 10: Voltage generated by paperboard TriboEG (in-plane mode) and voltage amplitude spectrum calculated by FFT at a gap of 1 mm.

Conclusion

Electric energy could be generated using a simple TriboEG with paperboard as a vibration transmission medium and PTFE as an electret. The final purpose of this research was to convert sonic waves such as environmental noise, voice, and sound to electric energy. Based on the dual wave nature of sound in which longitudinal and transverse waves propagate in a solid material, two types of TriboEGs were established in the out-of-plane and in-plane modes. These TriboEG systems successfully generated their highest voltage amplitude of 2.3 V at a forced vibration frequency of 46 Hz and highest output power 11.8 μW at 39 Hz both in the out-of-plane direction of the paperboard vibration. The other type of TriboEG momentarily generated its highest voltage amplitude of 8.2 V with manual strokes in the in-plane direction of the paperboard vibration. These results suggest that it is possible to harvest vibration energy from both longitudinal and transverse waves in environmental sound sources such as noise and the human voice. The practical displacement of paper surfaces due to sonic wave propagation is small even for transverse waves; however, microelectrodes and microelectrets printed on two sheets of paper with smoothly finished surfaces at a high resolution could be an electric power source for microelectronics in the future.

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