Energy harvesting from ambient air movements using nanotube sheet flutters

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ABSTRACT

We have developed a carbon nanotube sheet (CNT) flutter that is driven by ambient air movements, such as acoustic noise and gentle breeze, to produce electrical output power. When acoustic wave incidents on a nanotube sheet, it generates an oscillatory pressure of air molecules inside of the nanotube sheet aerogel, which in turns causes mechanical vibration of the nanotubes. The resonating vibration of the nanotubes converts to electrical energy via electromagnetic transduction providing a specific power of ~0.83 μW/Kg·cm^2 under an acoustic pressure of 53. The breeze-induced vibration caused by the interplay between the viscous drag and mechanical restoring forces of nanotubes also can be effectively converted into electrical power. By applying unregulated and intermittent air flow, the nanotube sheet flutter generates a specific power of ~10 μW/Kg·cm^2 from the gentlest breeze with a velocity of 0.16 m/sec.

Keywords: carbon nanotube, aerogel, energy harvesting, flutter, acoustic noise

1 INTRODUCTION

As the power requirements for microelectronics continue to decrease, ambient energy sources are becoming more feasible to increase the lifetime and capability of the devices by either replacing or augmenting the battery usage [1-3]. The energy scavenging technology offers two significant advantages over battery-powered solutions: virtually inexhaustible sources and little or no adverse environmental effects. Therefore, harvesting ambient energy from surrounding environment has attracted much interest in low-power technologies, including implanted medical, mobile electronic devices and powering RFID (radio-frequency identification) sensor nodes [4-6]. A variety of energy harvesting systems have been developed using a wide range of transducer type made of piezoelectric, thermoelectric and electrostrictive materials, etc [1, 6-8].

One of the most widely available forms of ambient energy could be air movements, such as acoustic noise and gentle breeze, which are essentially inexhaustible and everywhere. While previous researches have predominantly focused on extracting energy from preexisting vibrating host structures [5, 6, 9], the energy harvesting from ambient air movements should address not only the transduction of vibration to electrical energy but also the generation of vibrations from the kinetic energy of moving air as well. Piezoelectric cantilevers and composite diaphragms were demonstrated for the development of the air movement energy harvesters [1, 6, 10]. To effectively transfer the energy into an electromechanical transducer, a zigzag metal electrode, Helmholtz resonator and aeroelastic flutter were also employed [9, 11, 12].

A large part of energy harvesting problem involves coupling an available energy into transducers. Resonant systems could be the most effective, which produces the maximum power when the driving frequency matches the resonance frequency of the system. In practice, a low-resonance-frequency resonator tends to have a large size/mass, which is too heavy to be driven by relatively small energy of ambient air movements, while a small-size resonator has a high resonance frequency which is beyond ambient frequency levels. The amount of air movement energy is mostly available at low levels of frequency as well as low decibels or velocity in ambient environments.

In the present paper, we have developed a carbon nanotube sheet (CNT) flutter to produce electrical output from ambient air movements. Extremely low kinetic energy of moving air, for example, sound pressure in normal conversation or the gentlest breeze can generate mechanical vibrations of the nanotube sheet. The nanotube sheet flutter effectively converts the mechanical energy to electrical energy via electromagnetic transduction, enabling the nanotube sheet flutter for harvesting ambient air moving energy.

2 RESULTS AND DISCUSSION

We have fabricated a nanotube sheet flutter which simply consists of a nanotube sheet suspended between copper wire electrodes, and the sheet is placed in a homogeneous magnetic field as schematically depicted in Figure 1(A). Vertically-aligned multi-walled carbon nanotube (MWCNT) arrays were grown on an iron-catalyst-coated silicon substrate by chemical vapor deposition of acetylene gas. CNT sheets were drawn from a sidewall of the MWCNT forests using the dry-state spinning process [13, 14], which typically have a density of ~1.5 mg/cm^3, an

areal density in the sheet plane of ~1 to ~3 μg/cm^2, and a thickness of ~20 μm [13]. The as-produced CNT sheets were suspended between copper wire electrodes. In order to fix the CNT sheet on the electrodes, a thin silver paste was coated onto the electrodes, followed by drying under ambient condition. A homogeneous magnetic field (B) of 0.3 Tesla is applied across the nanotube sheet using a permanent magnet.

When a voltage (V) is applied to the electrode, the current flow through the sheet which is perpendicular to the magnetic field generates a flapping motion of the sheet driven by the Lorentz force (F_L). Figure 1(B-F) shows the optical images of vibrating motion at the first resonance frequency and transverse deflections with respect to applied voltages, respectively. The first vibrating resonance of the sheet was observed at 45 Hz in air under an applied AC voltage of 10 V (Figure 1(C)), which is quite lower than the resonant frequency (~1 KHz) measured in vacuum [13]. It indicates that air damping significantly affects on the actuation of the sheet due to its extremely low inertia and high specific surface area, actuating in a low Reynolds number regime [15, 16]. Static transverse deflections (δ_{max}) of the nanotube sheet were measured as 52 and 97 μm at the midpoint along the sheet length under DC voltages of 10 and 20 V, respectively (shown in Figure 1(D) and 1(E)). The observed voltage dependence of the static deflection is shown in Figure 1(F). The deflection increases approximately linearly with applied voltage ($\delta_{max} \sim F_L = B \cdot (V/R) \cdot L$, where R and L represent the resistance and length of the sheet, respectively), although a crossover occurs at higher voltages to a weaker dependence due to the stiffening effect by stretching the nanotubes with clamped at both ends [13, 17].

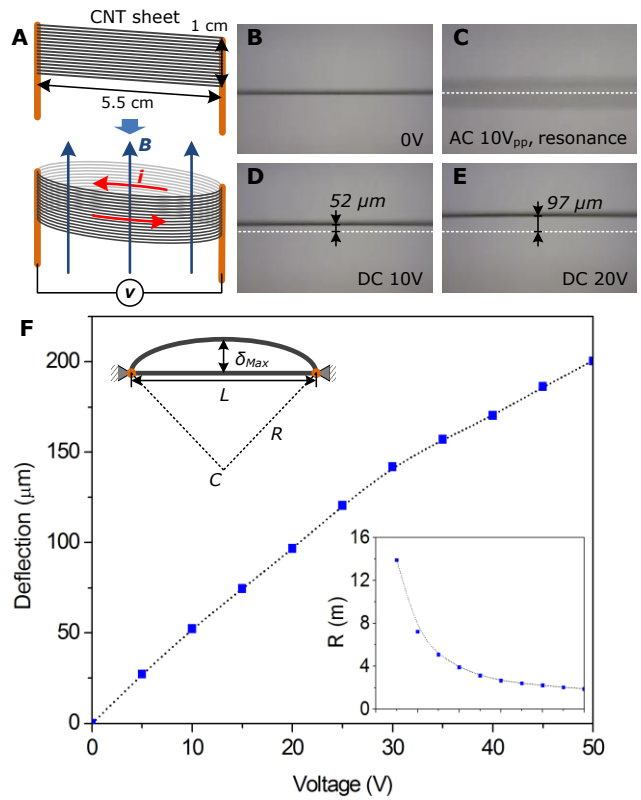


Figure 1. Electromagnetic actuation of a CNT sheet flutter

When acoustic waves propagate to a nanotube sheet, air molecules are moving in a direction that is parallel to the direction that the wave moves. The result of such longitudinal vibrations creates compressions and rarefactions (*i.e.*, pressure wave) within the air. The pressure wave is able to provide effective oscillating force for individual nanotubes of the sheet. The nanotube sheet flutter employs electromagnetic induction arising from the relative motion between a magnetic flux gradient and the nanotube sheet conductor. Therefore, the flapping motions of the nanotubes induced by acoustic wave can generate electric potential in the circuit. The sign convention of the generated voltage can be understood by the right-hand rule for a given direction of flapping motion and magnetic field, as schematically depicted in Figure 1(A).

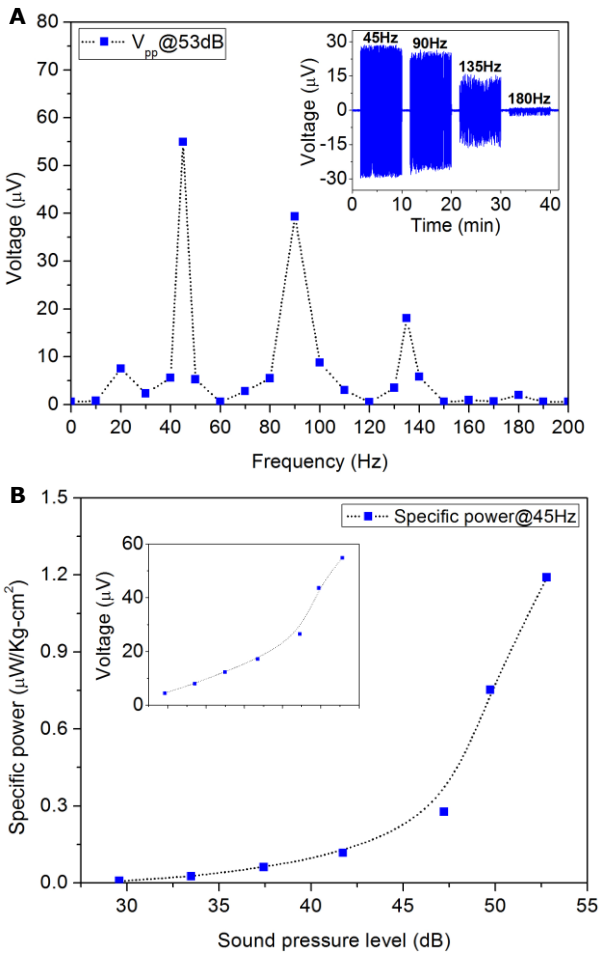
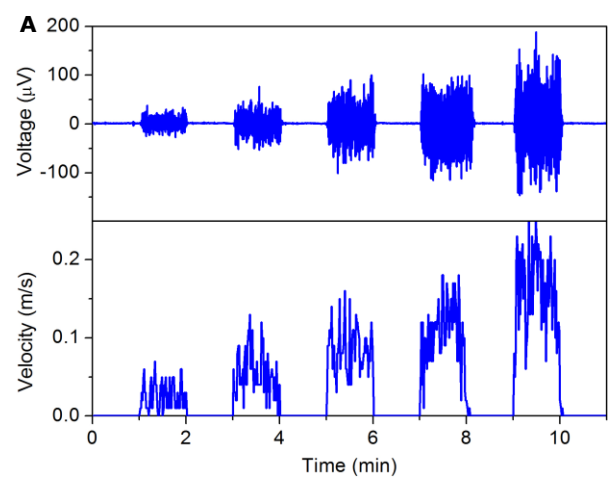


Figure 2. Energy harvesting from acoustic noise

Figure 2 shows the voltage generation from the flutter with respect to varying acoustic frequency with a sound pressure level of ~53 dB (Ref. 20 μPa). The decibel corresponds to ambient noise level from between normal conversation (~60 dB) and quiet office (~50 dB). It is clearly observed that the voltage output fluctuates much greater when the frequency of acoustic wave matches with the natural frequencies of the flutter. It is reasonable that even small acoustic pressure can produce large amplitude oscillations because the flutter stores vibration energy at a resonance frequency. The resonance frequencies at which standing waves are set up on the nanotube sheet are harmonically related, thus large voltages were also obtained at the higher mode of resonance frequencies; although the effective voltage decreases because the air damping characteristic of the higher-order resonance mode is usually superior to that with a lower-order mode [18].

In subsequent experiments designed to investigate acoustic energy harvesting capability with respect to sound pressure level at the first harmonic resonance (~45 Hz). The input acoustic wave was steadily increased in amplitude from 29 (corresponding to the sound level of whisper) to 53 dB. Such low-magnitude sound pressures are effectively converted to electrical energy with several tens of μV as shown in the inset of Figure 2(B). The specific output power generated from the acoustic energy was calculated as the product of the root-mean-square voltage and the resistance of the sheet ($P=V_{rms}^2/R$), normalized by the sheet area and weight. The specific power was measured as ~0.83 μW/Kg·cm^2 for an acoustic input pressure of 53 dB, as shown in Figure 2(B). An exponential increase of specific power was approximately obtained with respect to the increase of sound pressure level. It is reasonable that sound level is a logarithmic measure of the effective sound pressure of a sound relative to a reference value.

Gentle breeze in ambient condition tends to be unregulated and intermittent. The nanotube sheet is so flexible that it can convert the breeze energy into electrical energy even with the gentlest air movement. By applying unregulated and intermittent air flow, the effective voltage from 30 to 160 μV was obtained by the breeze power with a mean velocity from 0.025 to 0.16 m/sec, respectively. It is noteworthy that air moving with the velocity level could not be even a breeze, but just light air movement. The relationship between the specific output power from the flutter and mean velocity of the breeze is shown in Figure 3(B). The specific power of ~10 μW/Kg·cm^2 was generated for the gentlest breeze with a velocity of ~0.15 m/sec. With a relatively low velocity (under ~0.1 m/sec), the vibration of the sheet is originated from the interplay between the viscous drag and mechanical restoring forces. The sheet vibrates in accordance with an intermittent air flow, in which the voltage generation is linearly proportional to the velocity (see the inset of Figure 3(B)). At the low Reynolds number (Re < 10^{-4}), the Stokes approximation for creep motion flow simplifies the Navier-Stokes equation in which drag force is linearly proportional to velocity [15, 16]. High-frequency vibrations, known as aeroelastic instability or flutter [4], was also observed, which attributes to slight increase of the effective voltage when the breeze velocity is over ~0.1 m/sec. However the voltage generation switches to a weaker dependence as applied breeze velocity increases due to the stiffening effect of the nanotube sheet.



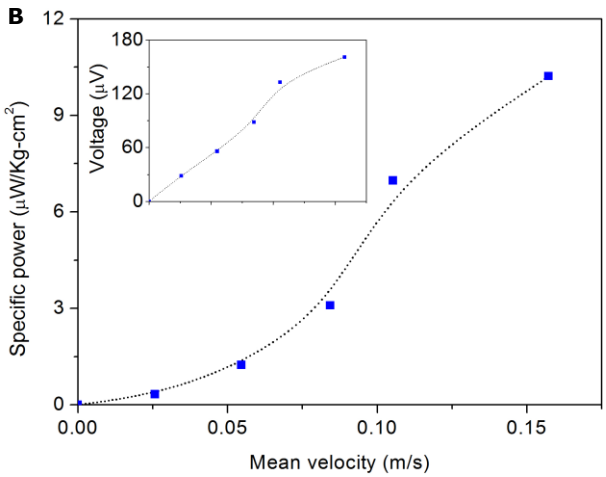


Figure 3. Harvesting breeze power

3 CONCLUSION

We have demonstrated the possibility of a carbon nanotube sheet (CNT) flutter for harvesting kinetic energy of ambient air movement, such as acoustic noise and gentle breeze. The resonating vibration of the nanotube sheets converts to electrical energy via electromagnetic transduction providing a specific power of ~0.83 $\mu W/Kg \cdot cm^2$ under an acoustic pressure of 53 dB. Moreover, the nanotube sheet flutter generates a specific power of ~10 $\mu W/Kg \cdot cm^2$ from the gentlest breeze with a velocity of 0.15 m/sec. Simple structure of the nanotube sheet flutter without any additional apparatus ensures the robust sustainability and stability of the electrical output. The ability to tune the sheet length and tension can be used for optimizing the performance by control the resonance frequency of the flutter. Optimization of the geometry and material properties is expected to yield significant performance improvement and promising applications.

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