POWERING ELECTRIC SYSTEMS USING CARBON NANOTUBE SPRINGS

Frances A. Hill[1*], Timothy F. Havel[1], David Lashmore[2], Mark Schauer[2], and Carol Livermore[3]
[1]Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA
[2]Nanocomp Technologies Inc., Concord, NH, USA
[3]Department of Mechanical and Industrial Engineering, Northeastern University, Boston, MA, USA

Abstract: The design, operation and performance of two batteries that store energy in mechanical springs made of carbon nanotubes are presented. The first battery extracts stored mechanical energy using a power regulation mechanism and piezoelectric energy conversion. The overall efficiency of the battery is low due to frictional losses in the power regulation mechanism. The second battery uses an electromagnetic conversion system to convert energy stored in the carbon nanotube spring to electrical output power, without regulating the rate of energy release from the spring. The second battery provides 42 mW of power with an overall energy transfer efficiency of 23%.

Keywords: Carbon nanotubes, spun yarn, mechanical springs, energy storage, electric batteries, generators

INTRODUCTION

This paper presents the first demonstration of electric batteries that store energy mechanically in springs made of carbon nanotubes (CNTs) and release the energy in the electrical domain. Energy storage in CNT springs has the potential to surpass both the energy density of electrochemical batteries and the power density of electrochemical capacitors [1-3] due to the 1 TPa stiffness of CNTs and their high elastic strain limits of up to 13% [4]. Ideal, defect-free CNTs are predicted to have a maximum energy density of 7.7×10^6 kJ/m^3 or 5×10^3 kJ/kg [1], three orders of magnitude greater than the energy density of conventional springs made of steel and higher than the 2×10^6 kJ/m^3 or 730 kJ/kg energy density of rechargeable lithium-ion batteries [5]. At the molecular scale, CNTs can function as ideal mechanical springs that store a great deal of energy for their size, but a single CNT does not store a useful amount of energy. Instead, this work focuses on storing macroscopic amounts of energy in large, ordered arrays of CNTs, with the objective of being able to supply power to drive macroscopic systems. Previous work has demonstrated spun yarn made of CNTs as an effective energy-storing spring for powering mechanical devices, such as fast-release slingshots, power-metering escapements, a kinetic energy harvester and mechanical watches [6, 7]. Advantages of CNT spun yarn as a spring material include a relatively ordered structure that allows many hundreds of millions of CNTs to be strained at once to achieve large-scale energy storage, and an amount of stored energy that can be tuned by changing the yarn's length and the number of CNTs in the cross-section.

The current work demonstrates the first use of CNT springs to provide electrical power. The design and performance of two electric batteries are presented. The first battery extracts stored mechanical energy using a metered-release system with piezoelectric energy conversion; the second battery uses an unmetered electromagnetic conversion system to convert energy from a CNT spring into electricity.

BATTERY WITH PIEZOELECTRIC ENERGY CONVERSION

The first battery stores energy in a CNT spring (CNT yarn stretched in tension) that drives a piezoelectric cantilever to convert the stored energy into electricity (Fig. 1). The spring is made of 12-ply CNT yarn. The yarn has a circular cross-section, a diameter of 50 μm, a linear mass density of 2 tex (or mg/m), a mean strength of 0.84 N/tex or 970 MPa, and a mean stiffness of 48.2 N/tex or 55.5 GPa. Scanning electron microscope (SEM) images of the yarn are shown in Fig. 2. Stretching the yarn in tension applies a torque that is transmitted by a series of transmission gears to an escapement mechanism that regulates the rate at which energy is released from the spring. During operation, one of the transmission gears periodically collides with a cantilever beam made of a PZT beam (Piezo Systems, T220-A4-203X) in series with a thin 6 mm long polymer tip and causes the cantilever beam to oscillate, thereby converting the mechanical energy to electricity. The voltage output by the piezoelectric cantilever beam is measured across a resistor. To maximize power, the resistance value is chosen to be $1/(wC)$, where w is the resonant frequency of the beam and C is the capacitance of the piezoelectric beam. The battery typically runs for 30-40 seconds when a 0.12% strain is applied to the spring. Fig. 3 plots an example of output power as a function of time. Each spike in Fig. 3a corresponds to voltage produced during each half-rotation of the balance spring, and each spike is made up of oscillations, as shown in Fig. 3b. The output energy from the system is calculated by integrating the power output from the cantilever beam during the period of operation. Applying a strain of 0.12% to the spring corresponds to input work done on the spring of 0.4 mJ, and the measured output energy is 4.15×10^{-8} J. Therefore, the efficiency of the energy transfer from the mechanical domain to the electrical domain is 0.01%.

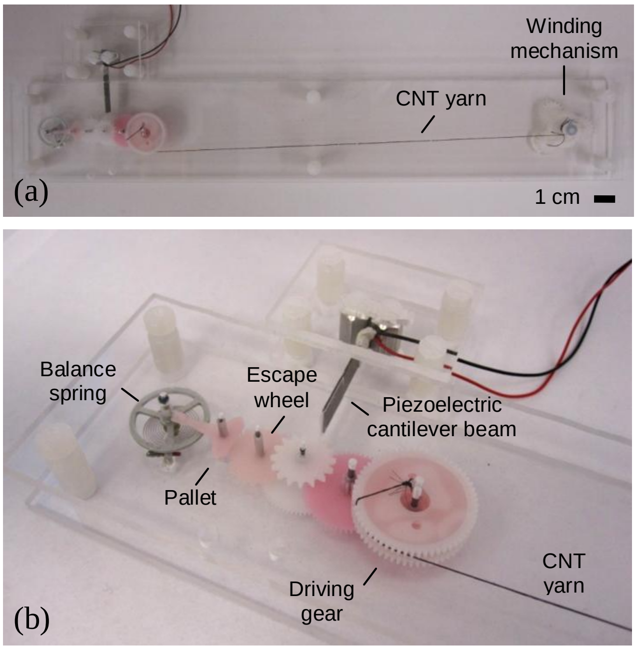

Fig. 1: CNT battery using a piezoelectric generator, showing (a) the entire system and (b) a close-up of the power regulation and energy conversion mechanism.

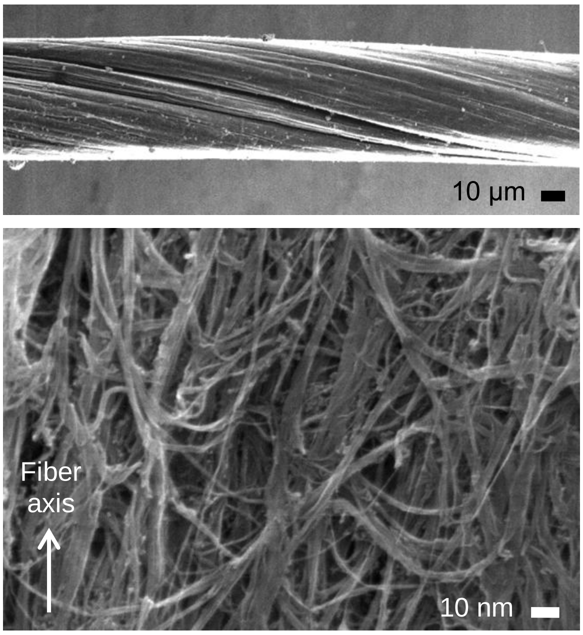

Fig 2: SEM images of the yarn used as the spring for the CNT battery with a piezoelectric generator.

An examination of the system reveals a number of areas where losses occur. Hysteresis losses can reduce the energy that is output from the yarn by as much as 30%. Energy is needed to drive the escapement mechanism (on the order of 10^{-5} J during 40 seconds of operation) and overcome the friction in the gears' bearings. The piezoelectric cantilever beams extract only a small fraction of the energy in the escapement mechanism, and piezoelectric conversion from mechanical to electric energy is less than 100% efficient. The sum of these losses is substantial, but it is expected that the greatest source of energy loss is friction in the escapement mechanism. The efficiency of the battery could be improved by redesigning the escapement mechanism to substantially reduce the friction in the gears, for instance by driving the gears using a torque rather than a force. A future design should also improve the coupling between the mechanical system and the piezoelectric cantilever. It is expected that future battery designs will be able to include a power regulation system while still maintaining high efficiency.

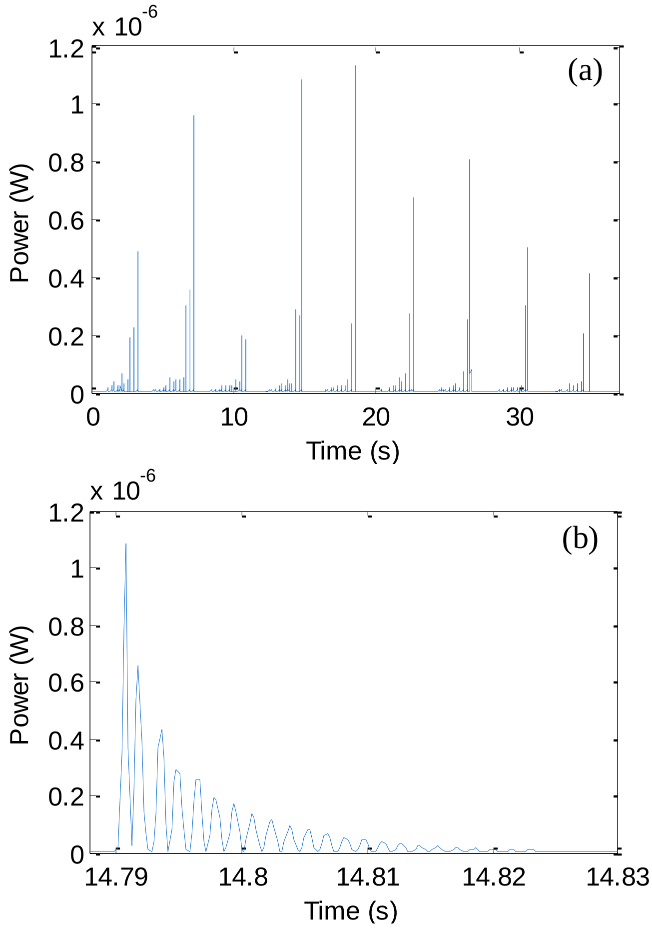

Fig. 3: Power output as a function of time for the CNT battery with a piezoelectric generator showing (a) the entire time of operation and (b) the oscillations in output power during the 40 ms following a collision between the cantilever beam and the gear.

BATTERY WITH ELECTROMAGNETIC ENERGY CONVERSION

The first electric battery was effective at regulating the power output from a spring, but its efficiency was low. A second electric battery was built for higher efficiency. To minimize losses, the second battery does not regulate power, and energy is released from the spring rapidly. An electromagnetic generator is used to convert the mechanical energy into electricity. Electromagnetic generators operate best when they are driven at high velocities, so such a device is well suited to convert the energy released rapidly from a spring. The battery is shown in Fig. 4. The battery stores energy in two springs made of CNT yarn, which are connected to the generator via a series of gears and arranged to minimize net forces and friction on the bearings by applying a couple to the driving gear. One end of each of the two springs is wound around a spool attached to a driving gear, while the other ends are attached to two fixed posts. Each spring is made of 6 strands of yarn plied together. A thicker yarn has been used in this battery in order to achieve high torques to drive the electromagnetic generator. The yarn used in this battery has a flat and wide cross-section, a linear mass density of 9.55 tex, and a mean strength of 0.48 N/tex or 970 MPa. SEM images of the yarn are shown in Fig. 5. The gear ratio from the driving gear to the generator shaft is 39:1. Energy is input to the springs by stretching them in tension, either by winding the driving gear or by applying a voltage to the generator to run it in reverse as a motor. To store the energy, the driving gear is manually latched in place. To release the energy, the latch is removed. The forces in the springs apply a torque to the gears, which rotate until the forces in the springs can no longer drive the generator. The voltage output by the generator is measured across a load resistor to calculate the power output. The power over time is integrated to measure the output energy and determine the efficiency of the system's mechanical to electrical energy conversion.

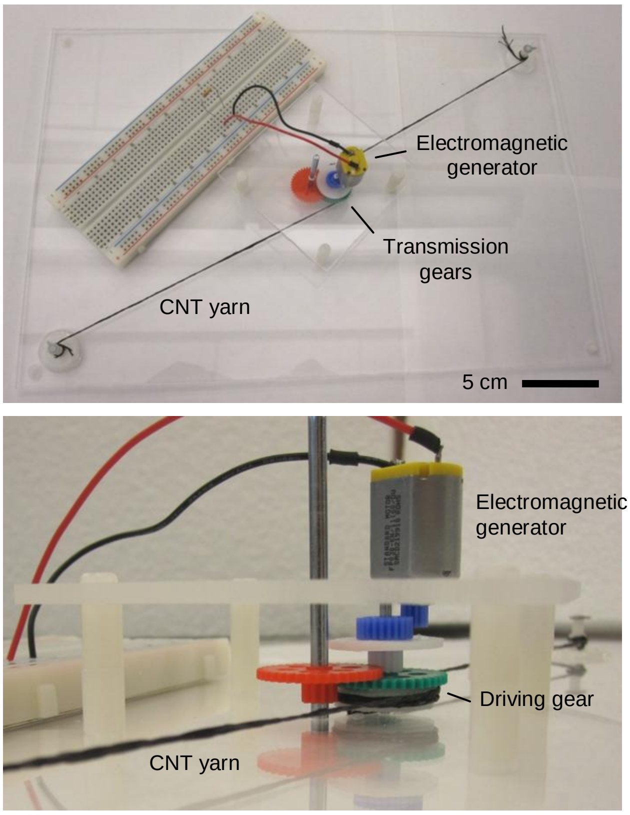

Fig 4: CNT battery using an electromagnetic generator.

To run the battery, the springs are stretched to a strain of 1.25%, which corresponds to input work done on the springs of 0.0146 J. The energy is released from the springs over a period of about 100 ms. Fig. 6 shows a typical plot of output power as a function of time. Fig. 7 plots the dependence of output electrical energy on the output load resistance. The maximum measured output electrical energy is 3.4 mJ with a 18 Ω load resistor. Using a 18 Ω resistance, the maximum output power from the generator is 0.15 W and the mean output power during the discharge time is 0.042 W, corresponding to a mean output power density of 4.7 MW/m^3 or 2.5×10^3 W/kg, considering only the mass and volume of the spring. Energy was released from the spring and converted to electricity at a density of 885 J/kg or 1.77×10^6 J/m^3, considering only the mass and volume of the spring. The maximum efficiency of the energy transfer from the work done on the yarn to the electrical output is 23%.

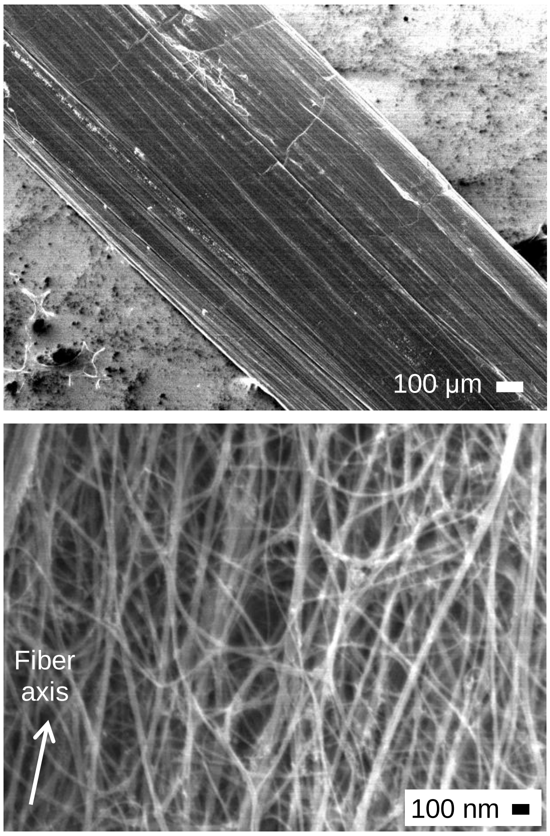

Fig 5: SEM images of yarn used as the spring for the CNT battery with an electromagnetic generator.

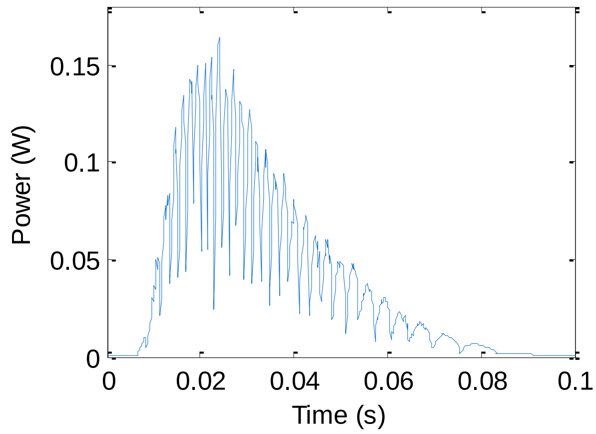

Fig. 6: Power output as a function of time for the battery with an electromagnetic generator.

The energy density and power density of the battery with the electromagnetic generator and of ideal CNT springs are plotted on the Ragone plot in Fig. 8. The plotted energy density and power density of both ideal CNT springs and the CNT-based battery take into account the mass and volume of the spring alone, without considering the mass and volume of the supplemental architecture needed to operate the springs. The plot shows the remarkable potential of energy storage in ideal CNT springs. The average maximum energy density that can be achieved in the CNT yarn is measured to be 4.2 kJ/kg [7], and this energy density is shown as a dashed line in Fig. 8. To date, this is the upper limit on the energy density that a battery that stores energy in CNT yarn can achieve. The performance of the demonstrated CNT battery falls short of the energy density limit of the yarn because of frictional losses within the battery, the need for further device optimization, and a strain applied to the spring in the battery during winding that is below the strain limit of the material. The energy density limit of the CNT yarn falls short of the ideal CNT energy density because of non-idealities in the yarn structure and properties; further improvements in the structure and energy storage capacity of the yarn will additionally lead to superior battery performance.

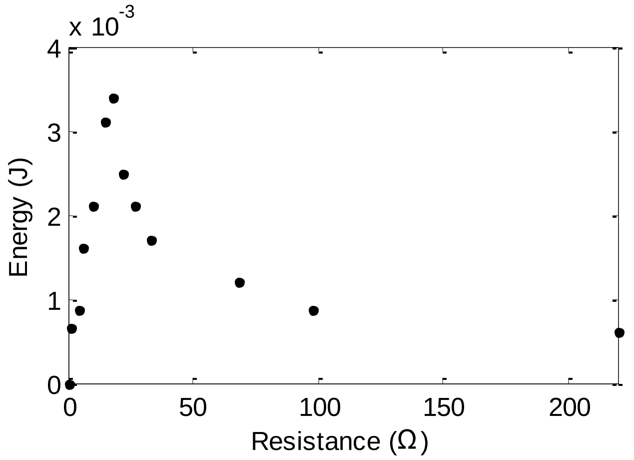

Fig. 7: Output electric energy as a function of output load resistance.

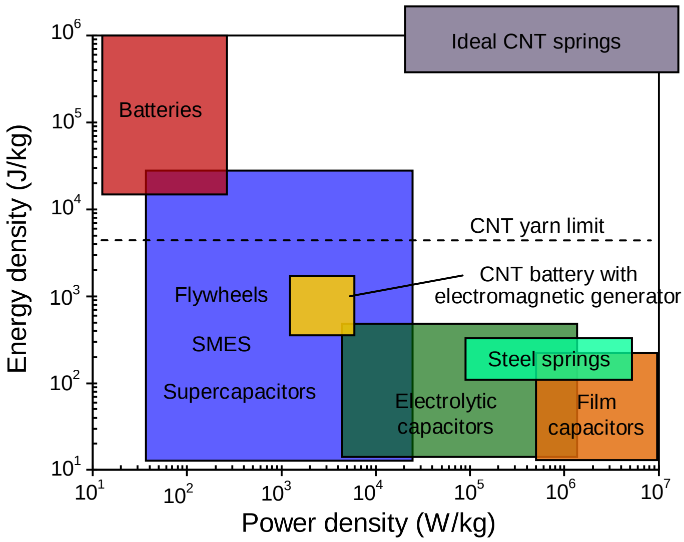

Fig. 8: Ragone plot comparing the energy density and power density of ideal CNT springs, the CNT-based battery with electromagnetic energy conversion, and conventional energy storage technologies [7, 8].

CONCLUSION

Springs composed of highly ordered groupings of CNTs form the basis for a new class of promising energy storage devices, offering a combination of high energy density and high power density. Electric batteries that store energy in CNT springs may offer an energy density comparable to conventional batteries, with added advantages of high power density and stability under extreme conditions, such as high temperature or high pressure. The two batteries that have been designed are initial demonstrations of ways to store energy in a spring and output that energy as electricity, and these batteries provide design guidelines for a next generation of improved devices. The two batteries are not yet optimized for maximum efficiency or overall energy density and power density, nor do they demonstrate the limits of energy storage that can be achieved with CNT springs. The battery with piezoelectric energy conversion shows that the rate of energy release from a CNT spring can be controlled using an escapement mechanism, though frictional losses should be reduced in future designs. The battery with electromagnetic energy conversion provides 42 mW of power with an overall energy transfer efficiency of 23%. Further system improvements are expected to increase the batteries' power density and efficiency.

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