Regenerative braking systems with torsional springs made of carbon nanotube yarn

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Abstract: The demonstration of large stroke, high energy density and high power density torsional springs based on carbon nanotube (CNT) yarns is reported, as well as their application as an energy-storing actuator for regenerative braking systems. Originally untwisted CNT yarn is cyclically loaded and unloaded in torsion, with the maximum rotation angle increasing until failure. The maximum extractable energy density is measured to be as high as 6.13 kJ/kg. The tests also reveal structural reorganization and hysteresis in the torsional loading curves. A regenerative braking system is built to capture the kinetic energy of a wheel and store it as elastic energy in twisted CNT yarns. When the yarn’s twist is released, the stored energy reaccelerates the wheel. The measured energy and mean power densities of the CNT yarns in the simple regenerative braking system are up to 4.69 kJ/kg and 1.21 kW/kg, respectively. A slightly lower energy density of up to 1.23 kJ/kg and a 0.29 kW/kg mean power density are measured for the CNT yarns in a more complex system that mimics a unidirectional rotating regenerative braking mechanism. The lower energy densities for CNT yarns in the regenerative braking systems as compared with the yarns themselves reflect the frictional losses of the regenerative systems.

1. Introduction

Many portable devices are limited by the lack of power supplies that offer both high energy density and high power density. Fuel cells and batteries offer high energy density but poor power density, whereas mechanical springs and capacitors have high power density but low energy density [1]. Fuel-burning devices can offer both high energy density and high power density, but their efficiency decreases at a smaller size scales, increasing their environmental cost. Carbon nanotubes (CNTs) offer an appealing alternative. Their low relative density (1.33-1.4 times of water) [2], high stiffness (1 TPa) [3], and high extendibility (up to greater than 13% elastic strain in [4]) offer exceptional performance as elastically-deformed, energy storing springs for small scale systems. Idealized continuum modelling of individual CNTs under load has estimated the upper bound on energy density at 5000 kJ/kg under the optimum achievable tensile loading. This energy density, if achievable, would be more than 1000 times the energy density of steel springs, and more than 5 times greater than that of lithium-ion batteries. In addition, CNT springs offer the potential for high power operation just as traditional mechanical springs do [1, 5], potentially enabling solutions for portable systems requiring both high energy density and high power density.
In practice, the energy densities of elastically-deformed CNT springs fall below ideal maximum values. For example, the CNT springs of [6] show an average energy density of 4.2 kJ/kg under incremental cyclic tensile test, along with demonstrated peak power densities of up to 170 kW/kg for quick-release sling-shot devices and mean power density of 2.5 kW/kg for slow-release, metered systems. Part of the challenge lies in scaling up from the single-CNT scale to the milli and macro scales. Using CNT yarns instead of individual CNTs increases the total energy stored at the expense of reduced energy density; the yarn’s non-ideal inner structure permits non-uniform loading, slippage, and defects to reduce its performance under load. For systems like those of [6], a second challenge of effective energy release lies in the mismatch between the characteristics of the power supply (which offers high force and extremely small stroke) and the load (which typically requires lower force and higher stroke, except for applications that require the highest possible power density).

The present research employs CNT springs in torsion rather than in tension to address some of the challenges of CNT springs for driving mechanical loads. Loading CNT springs in torsion can increase the stroke (at the expense of slightly lower peak power) and offer better matching between the power supply and load characteristics. The driving torques produced by torsional loading couple readily into the rotating systems that comprise a great many common machines. Although torsional loading may in theory offer reduced energy density as compared with more spatially uniform axial loading, the reduction may be moderated by a reduction in slippage as the originally untwisted fibers become ever more tightly packed with twisting. In addition, torsion applied as in the present experiments (with fixed separation between the yarn’s ends) can also result in more local axial stretching, thereby enhancing energy density for torsional actuation. Thus, torsional actuators can offer improved performance for applications that require longer stroke and are tolerant of slightly lower peak powers.

Previous studies of CNT assemblies under torsion have focused on systems in which the ends of the CNT assemblies are free to move closer together and further apart as the assembly twists and untwists. The research of [7, 8] examined several different hybrid, coiled CNT yarn structures, typically with hierarchical twist architectures, as contractile linear actuators that operate by the twisting and untwisting of CNT yarns. The largest contractile energy density in [7] was 1.36 kJ/kg at 5.6% linear contraction. In [8], electrolyte-filled twist-spun CNT yarns were demonstrated as torsional CNT artificial muscles that output a combined contractile and torsional power density of 0.92 kW/kg and 0.062 kW/kg, respectively. Additionally, a torsional experiment in which CNT fibers support a rotational pendulum at a height that is free to vary with rotation demonstrated up to 24% elastic shear strain [9]. In [10], CNT yarns that were overtwisted to form entanglements and released to rotate a cylinder demonstrated an optimum 8.3 kJ/kg energy density and a power density of less than 1 kW/kg.

These tests suggest that CNT yarns under torsion may offer comparable energy density to CNT yarn under tensile loading, but the performance of twisted yarns subject to a length constraint has not been explored.

Experiments were performed to better mimic the behaviour of real-world systems in which the ends of a torsional spring are tethered at a fixed separation; the fixed-separation approach may also increase energy density by maximizing energy stored in the stretching of CNTs that follow a helical path around the CNT yarn. To characterize energy storage under these conditions, a custom-built torsion tester (figure 1) twists one end of a yarn relative to the other while maintaining nearly constant separation between the yarn ends and measuring reaction torque and axial force.

**Figure 1.** A custom-built torsional testing system with a torque transducer, an axial force transducer, a rotary actuator, two sample fixtures and three linear positioners.
2. Characterization of mechanical behavior under torsional loading

Continuous untwisted CNT yarns (figure 2A, 2B) are grown by a gas phase synthesis process that incorporates a free-flowing catalyst. They are comprised of both single-walled and multi-walled CNTs with diameters typically between 3 nm and 8 nm. The untwisted yarn has typical cross-sectional dimensions of 1 mm x 130 µm and has a mean linear mass density of 9.55 tex (where 1 tex = 1 mg/m). CNT yarn specimens with a typical gauge length of 25 mm are attached to sample fixtures using epoxy (Pacer Z-Poxy). The fixtures are then mounted on the torsion tester, and their axial spacing is adjusted using a micropositioner to remove slack in the yarn and achieve a small, starting axial preload of 0.2N. A rotary actuator (Oriental Motors DG85) twists the yarn at a constant rotational speed, while the torque transducer (Vibrac mini static 0.05 oz-in) and load transducer (SMD S250-5kg) detect the resulting torque and axial force. Figures 2C and 2D show the resulting yarn structure. The compliance of the transducers is much smaller than the compliance of the yarn, so that the supports may be approximated as rigid with fixed separation. The torque, force, and angle of rotation are collected by a NI USB-6221 BNC DAQ device via a Labview interface.

CNT yarns were tested under incrementally-increased torsional loading. The total rotation angle is increased from zero in increments of five turns until failure. The results are repeated five times per increment before increasing the number of rotations in the next increment. Figure 3 plots the results of a cyclic torsional loading of a 25.4 mm-long, 2-ply CNT yarn. The raw data include smaller torque variations with the periodicity of the rotation; these variations reflect a small axial misalignment of the motor and torque transducer. For clarity, the data of Figure 3A have been post-processed to show only the overall incremental loading performance. The rotational speed is 15 turns/min, and the yarn rotates to 30 turns before failing on the way to 35 turns. During loading, the yarn transitions from a non-circular cross-section to a “twisted ribbon” structure that approximates a circular cross-section (figure 2C). The maximum specific torque is measured at 540 N-m/kg. The maximum extractable energy density of 6.13 kJ/kg is calculated by integrating the area under the untwist curve of the fifth cycle in the largest increment loading group. Among the six specimens, the average angle of twist per unit length is more than 7400 rad/m, average input and output energy efficiency is about 53%, and average energy density is about 3.82 kJ/kg, comparable to the 4.2 kJ/kg energy density in tension [5].

Figure 3. Torsion test data for a 25.4 mm long, two-ply CNT yarn cyclically twisted to failure with 5 cycles per increment (5 turns per increment) at the rate of 15 turns/min until breakage. (A) Plot of specific torque vs. rotation shear strain (angle per length); (B) plot of energy density of each twisting cycle; (C) plot of energy efficiency of twist and untwist of each cycle.
The high energy densities, comparable to those obtained for pure tension, might initially seem surprising. Because strains are much larger near the periphery of a torsionally-loaded shaft than they are near its center, twisting is not expected to load all of the material to its limits, resulting in a lower energy density than in axial loading. However, twisting of a filamentary structure with fixed separation of the ends results in stretching of the helically-wrapped filaments as described above and in [11]. In practice a given filament will sample both the inner and outer regions of the yarn’s cross-section, and slippage between the filaments offers the opportunity for filaments to be loaded to a more spatially uniform average axial stress, potentially increasing energy storage as compared with torsional loading of a shaft. The twisted yarn’s high performance may also reflect increased load transfer and reduced slippage due to radial compression of the yarn under large torsional loads. The yarn’s structural reorganization under loading is apparent in figure 3A, in which the first loading cycle for each increment creates a new torque-angle loop, which is relatively stable over continuing load cycles at that level of deformation. Yarn reconditioning is therefore most apparent in the first load cycle at a given level, whereas a more stable hysteresis loop appears in the subsequent cycles. Figures 3B and 3C plot extractable energy density and energy efficiency as calculated from the hysteresis loops of figure 3A. Although energy density decreases over the load cycles at each increment, efficiency increases, demonstrating the structure’s reorganization into a more stable configuration.

3. Regenerative systems driven by CNT yarn

Two model regenerative braking systems that capture energy in and deliver energy back from CNT torsional springs were demonstrated. In the first demonstration, the CNT yarn couples directly to a wheel on a shaft (figure 4A). Energy is stored in the actuator by twisting the disk quickly to an initial high speed to simulate braking and storing the kinetic energy in the twisted CNT yarn until the speed drops back to zero. The wheel is then allowed to accelerate freely under the yarn’s actuating torque. Axial force is measured by a load cell as described in section 2. The rotation of the wheel is measured by an optical sensor (Philtec RC171) that detects passage of periodic features on the disk’s surface, and the corresponding angular velocity and rotational acceleration are calculated from the measured rotation angle. The extracted energy density is calculated from the maximum measured kinetic energy of the wheel (determined from the measured angular speed and the rotational inertia of the wheel and the shaft) and the mass of the yarn. Because some of the extracted energy is lost to friction, this approach underestimates the energy density of the energy-storing yarn. The measured acceleration similarly underestimates the effects of the yarn’s driving torque, because it represents the difference between acceleration of the wheel by the yarn and the deceleration of the wheel by friction. A lower bound on maximum power density may nonetheless be extracted from angular velocity, angular acceleration, and moment of inertia using the results shown in figure 4. The resulting values for the case of figure 4 are a maximum energy density of 4.69 kJ/kg and a mean power density of 1.21 kW/kg over a 3 s release time (figure 4B). The corresponding stroke was large, at 14 turns.

Figure 4. (A) Schematic diagram of the first regenerative braking test system in which the CNT yarn couples directly to a wheel on a shaft, and (B) plot of wheel angular velocity and power density vs. time. The data are determined from measured rotation angle vs. speed accelerating time data, when the wheel of figure 4 is driven by a 6 cm-long, 2 ply CNT yarn.
The second model regenerative braking system (figure 5A) also employs a single wheel. However, it is equipped with a ratchet unit that couples to the yarn by rotating the wheel to wind the spring, decouples it with the ratchet gears for transmission gear changeover, and enables the yarn to drive the wheel to release the energy in the same rotation direction as during energy capture. Figures 5B and 5C plot the kinematic variables over time from a test using a 6.2 cm, 4-ply CNT yarn. Figure 5B shows the initial angular velocity of 54.3 rad/s is decelerated to zero at time 6.7 s by storing energy into the CNT spring; then the CNT spring starts to reaccelerate the wheel at time 80 s. The maximum angular velocity is 18 rad/s, with a total acceleration time of 3.2 s. The 0.29 kW/kg mean power density is calculated from the system’s moment of inertia, angular acceleration and angular velocity over the duration of energy release (80-83.2 s). The 1.23 kJ/kg energy density is calculated from the maximum velocity after energy release, the moment of inertia, and the mass of the wheel and shaft. Energy and power density are slightly lower than in the first demonstration due to larger frictional damping.

4. Conclusion
CNT yarn has been demonstrated as large stroke, high energy density, high power density torsional springs for regenerative braking systems with fixed separation between the spring ends. The maximum energy density measured in torsion tests is up to 6.13 kJ/kg. Demonstrations of regenerative braking using untwisted CNT yarn as the energy-storing medium obtain energy and mean power densities of the CNT yarns of up to 4.69 kJ/kg and 1.21 kW/kg, respectively. Advances in CNT yarn preparation and system design can offer the potential for still higher energy and power densities in the future.

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