ADVANCED MATERIALS

Carbon-Nanotube-Based Electrical Brush Contacts

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Sliding electrical contacts are ubiquitous in electric motors and various forms of monolithic metal – carbon composite brushes and filamentous precious metal brushes represent the highest performance materials available. There is a tremendous opportunity to develop a whole new class of high-performance brush contacts using aligned films of carbon nanotubes, possessing super-compressibility,[1] high electrical and thermal conductivity,[2–3] mechanical strength,[4] tunable friction behavior,[5] and environmental insensitivity. Here, we demonstrate the feasibility of aligned multiwalled carbon nanotube (MWCNT) brushes as a new and superior alternative to the traditional high-performance brushes for electrical contacts. These brushes have been shown to provide stable low-noise operation for extended sliding durations. We investigate both the direct-current (DC) and alternating-current (AC) properties of these nanotube brush contacts and demonstrate their reliable low-noise electrical performance as rotating axels as well as sliding contacts in motors. Our results demonstrate a new materials approach to produce stable, intimate, and ultralight electrical brush contacts at moving interfaces.

Both the DC and AC current-carrying properties of macroscopic CNT contacts were investigated. The most common applications for sliding contacts are brushes that carry electrical current in motors and generators.[6] Solid brushed-type electric motors are still widely used and desirable because of their intrinsically low magnetic fields and noise and potential for high power density applications. The low cost, ease of controlling the speed, and demonstrated operation over a range of challenging conditions make brushes popular choices for electric motors. In most applications the brushes are fixed on flexible cantilevers that are designed ideally to provide compliance and low applied normal load, yet to follow the rotational error motions of the shaft without bouncing (an extremely detrimental process that leads to arcing and rapid brush deterioration).[6,7] The relatively high rigidity and high mass of solid brushes causes a paradoxical situation in brush design, where low loads are desirable for low frictional losses and long life, but high loads are desirable for stable and low contact resistance.[6]

Carbon nanotubes (CNTs)[2,8] are interesting materials with high electrical conductivity and mechanical compliance and these properties have been exploited in nanoelectromechanical systems and nanoelectronic devices.[9–11] Various applications for nanotube brushes have been suggested[12] but the use of nanotube brushes as contacts has not yet been exploited. Large blocks of ordered CNT films (or brushes) can today be synthesized directly by catalytic chemical vapor-phase deposition (CCVD) methods.[13,14] Brushes with a large foot-print area of up to several square centimeters and with thicknesses beyond several millimeters have already been reported.[15] The attractive mechanical and electrical properties of these CNT brushes have been exploited in a range of applications such as super-capacitor electrodes,[1,16] super-compressible springs,[17] multifunctional nanobrushes,[12] and chip-cooling elements.[18] The question we address here is how good nanotube brushes are for electrical contacts in movable motor parts and whether they could be utilized as next-generation brush contacts, i.e., utilized as sliding and rotating electrical contacts in harsh environments.

To demonstrate the feasibility of sliding CNT brush contacts (Fig. 1), the ordinary solid brushes of an electric motor made of a 40/60 wt.% carbon–copper composite were replaced with blocks made of MWCNT forests grown by CCVD (see Experimental). The nanotube materials were mounted on flexible brass cantilevers to form brush-type structures, which were brought into contact with the slightly modified (see Supporting Information, Fig. S1b and S1c) commutator of the electric motor (Johnson Electric, ~6 500 rpm at 12V). Optimal pre-pressing force (72 mN for CNT and conventional brushes) was set for both brushes with 2 translation stages controlled with micrometer precision. (see Supporting Information, Fig. S1a).

Under constant current conditions (14 mA, with 12 V compliance voltage), the electrical contacts provided by the MWCNT brushes resulted in more steady and regular voltage values with significantly less noise than that measured for ordinary carbon–copper composite brush. The smaller fluctuation in the voltage can be attributed to the smooth sliding of the soft nanotube film on the irregular rotating surface, as the films conform to the non-uniform roughness of the rotating commutator surface. As a consequence of rotational motion, both shear and compressive forces are reacted by the brushes. The effects of the commutator bar and trailing edges are clearly visible as they result in voltage drops and sharp peaks in the time series graphs. Accordingly, small deviations are visible from the expected

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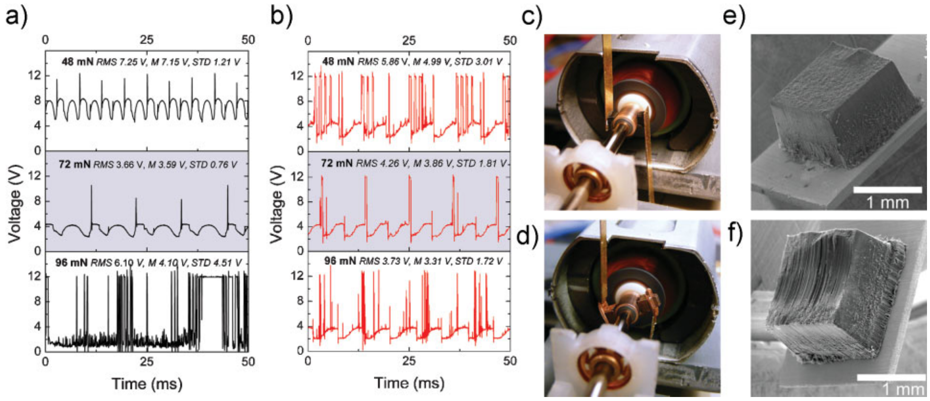

Figure 1. MWCNT and conventional brushes in electric motors. Voltage fluctuation measured during normal operation when a constant current was maintained for a) MWCNT and b) commercial graphite–copper composite brushes. The curves correspond to the measurement results taken when 48, 72, and 96 mN force were applied from the top to the bottom, respectively. Photographies of the experimental arrangements of c) the MWCNT and d) conventional brush setups. FESEM image of the CNT brush-on-brass cantilever assembly (e) and the wearing after several hours of operation (f).

behavior on the voltage fluctuation curves for both types of brushes, and the somewhat different results for the individual brushes can be explained by a slight alteration in the contact angle and by the direction of rotation that produces slightly different forces for each brush. Additionally, both types of brushes exhibit higher bulk stiffness in comparison to the cantilever spring that dominates the macroscopic normal forces (smooth rounded shape in Fig. 1a,b). However, clear differences for the brushes are seen for the tangential stiffness where the cantilevers and solid brushes are stiff but the CNT brush is soft (shear modulus ~7 MPa[12]). Mechanical chopping by bar edges causes significant bouncing and noise for the solid brush while a CNT brush conforms to the irregularities and changes in friction forces by shear deformation. Using the optimal 72 mN pre-stress, the same current was maintained by similar voltages (~3.5 V, corresponding graphs are highlighted with grey color on Fig. 1a,b) for the two setups. By introducing excessive pre-stress, which generates higher shear forces, a drastic increase of instability was seen especially for the nanotube brushes as a consequence of intimate interaction with the commutator surface and severe bouncing at the interfaces. However, at the same time, decreased contact resistance was achieved. In contrast, a lower force (48 mN) exhibits a double frequency signal (Fig. 1a) as the brush has more freedom to run off the surface, creating continuous bouncing and intermittent contacts with the commutator.

The MWCNT brushes were fully operational throughout the time of the experiments, usually several hours, but also up to five days of testing with no considerable wearing and failure (see the video in the Supporting Information). After one million motor revolutions, a minor wear appears (Fig. 1e,f) on the surface as the edges of the rotating commutator axle mill up and re-align the top-most region of the nanotube block. No fracture, detachment, or any other considerable structural damage of the nanotube brushes was observed. Beyond the mechanical robustness of carbon nanotubes their high heat conductivity may play an important role to prevent structural defects. Local dimpling of the brushes seen during repeated contact cycles seem to disappear by self-healing, as seen before.[1]

Although the above experiments technically showed that the CNT brushes outperform commercial brushes, it is difficult to obtain relevant data for the electrical noise and contact resistance that arise from the nature of the two kinds of brushes in contact with "smooth" rotating conducting surfaces. To study these properties the rotating axle of the electric motor (Johnson Electric, ~3600 rpm at 12V, with a typical surface roughness of less than 1 μm for high-gloss stainless steel), instead of the commutators as used above, was brought in contact with the two types of brushes (Fig. 2). A current source was applied (10 mA, Keithley 6221) through the brush–axle–brush contacts and the bias voltage was measured with an oscilloscope (Agilent 53622A). By applying the optimal pre-stress (144 mN in this case for the lowest resistance and standard deviation), the nanotube contacts show an almost an order of magnitude lower contact resistance (corresponding graphs are highlighted with grey color in Fig. 2a,b) and a two orders of magnitude lower noise intensity compared to the monolithic brush used in the experiments (Fig. 2c). In general, the power density spectra show similar frequency characteristics for the both brushes derived from similar fixture and spring constant of the cantilevers. Therefore,

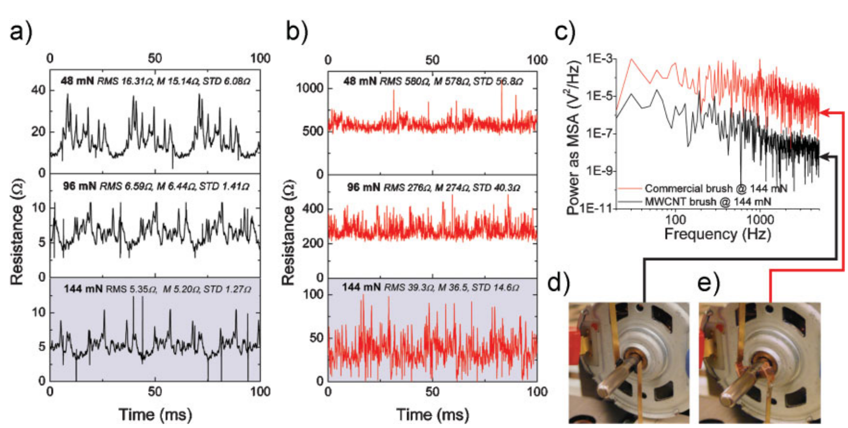

Figure 2. Electrical signal fluctuations measured on rotating axles contacted by MWCNT and conventional brushes. a,b) Resistance fluctuation measured on MWCNT and commercial brushes setups, respectively. c) The power density spectra indicate superior noise characteristics of nanotube brush contacts in comparison with solid carbon–copper composite brushes. d,e) Optical images of the experimental arrangements with carbon nanotube and conventional brushes, respectively.

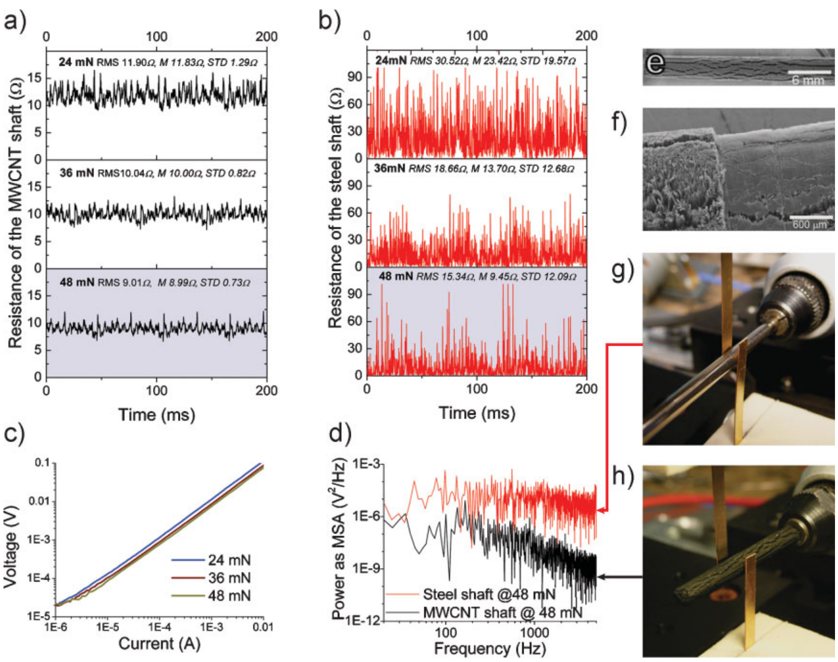

Figure 3. Electric contact with rotating MWCNTs. a,b) Resistance fluctuation for MWCNT and steel axles, respectively, measured under constant current conditions and with different pre-stress forces. c) *I–V* characteristics of the rotating MWCNT axle at different forces. d) Power density spectra calculated from (a) and (b). e) The as-grown MWCNT film on a quartz rod. f) The shallow stench after usage. g,h) Optical images of the experimental arrangements performed with a steel axle and carbon-nanotube-coated quartz axle, respectively.

resonances of the both brush setups are similar. However, slightly lower bending-resonance frequencies were detected for commercial carbon–copper composite brush because of the greater density (~2.84 g/cm^3) and mass compared to the MWCNT brush (~0.3 g/cm^3).

In analogy to the sliding nanotube brushes, another type of rotating contacts can be made from aligned nanotube films where the nanotubes are grown on cylindrical objects. This type of contact has less trivial application compared to the brush contacts. However, applications such as unipolar generators, motors, and a wide variety of electromagnetic launchers require high-current-density sliding electrical contacts against a smooth counter surface. To demonstrate such contacts (Fig. 3), which must exhibit low noise and small contact resistance, nanotube films with a thickness of ~1.0 mm were grown (Fig. 3e) on quartz rods (length of 40 mm and diameter of 2 mm, Goodfellow). The rods comprising the nanotube forests were then contacted with flexible brass cantilevers serving as electrodes (Fig. 3g). An ordinary steel axle was contacted in a similar fashion for comparison. After a few minutes of operation, a visible wear in the location of the contact appears on the nanotube axle as the brass cantilever slightly compresses the nanotube film resulting in an ~100 μm deep trench (Fig. 3f), this change in the geometry did however not result in operational failure.

The contacts between the cantilevers and rotating nanotube film showed linear *I–V* behavior (Fig. 3c). Low noise operation was demonstrated by using a current-stabilized source (10 mA, Keithley 6221) through the brush-axle-brush contacts. The bias voltage was measured with an oscilloscope (Agilent 53622A). By applying the optimal pre-stress (48 mN) value, the nanotube contacts have slightly lower contact resistance (corresponding graphs are highlighted with grey color on Fig. 3a,b) and significantly less noise (Fig. 3d) compared to the brass–steel–brass contact. At higher frequencies the carbon nanotube contact is less noisy as its power spectrum is close to $1/f^2$ shaped in the $f > 100$ Hz region. At the same time the power spectrum for the steel axle setup shows almost white noise. The dissimilarity of noise spectra demonstrates the advantageous damping properties of the MWCNT film, as well as the good electrical contact provided by a compressed springlike nanotube contact.

The damping, super-compressibility, low-elastic-modulus electrical and thermal conductivity are also ideal for high current-density switching applications. There is a demand for low-load and high-frequency direct contact DC switches; these devices have proven to be very challenging due to constriction resistances, very high current densities, and temperatures that develop in the local a-spots.[19] The MWCNT films were examined in hot switching experiments with a gold pin contact to establish the stability of the electrical contact during the repeated cyclic contacts. There is a similarity between the sliding electrical contact and repeated contact applications, such as switches. In both of these current carrying applications, we believe that the MWCNT local contacts are elastic and are distributed across the footprint of the contact. The high elastic modulus of traditional brush and switch materials and the light loads used in practice causes the real area of contact to be many orders of magnitude lower than the apparent area of contact.[19] The super-compressibility and conductivity of MWCNT therefore provide a unique opportunity to have pressed elastic contacts and high interfacial contact area with good electrical conductivity even at light loads. Fig. 4a shows a schematic of a contact switch apparatus where a vertically aligned MWCNT film forms the foundation for repeated contacts with a gold coated glass pin. Due to the compliance and super-compressibility[1] of these films the computed contact areas are tens of thousands times greater than bulk materials.[19,20] Figure 4b shows the robustness of these films and stability of the electrical contact (seen by the constant contact resistance shown in Fig. 4b) to prolonged hot-switching events; over 100 000 cycles were performed over 4 days in open air (experiments on thin ~1 μm gold-coated silicon samples did not survive the first cycle at open circuit voltages above 1 V).

In summary, carbon nanotube blocks were used as extended brushes for creating sliding or point contacts in this work. The feasibility of the nanotube films mounted on flexible brass cantilevers and directly grown on quartz rods in electromechanical applications were exhibited, where the structural integrity, compressibility, and good electrical conductivity of aligned macroscopic nanotube films were exploited. The results showed that the nanotube films are certainly appropriate alternatives of conventional carbon-based or solid metal "brushes" as a sliding/rotating electric contact. The soft but at the same time durable

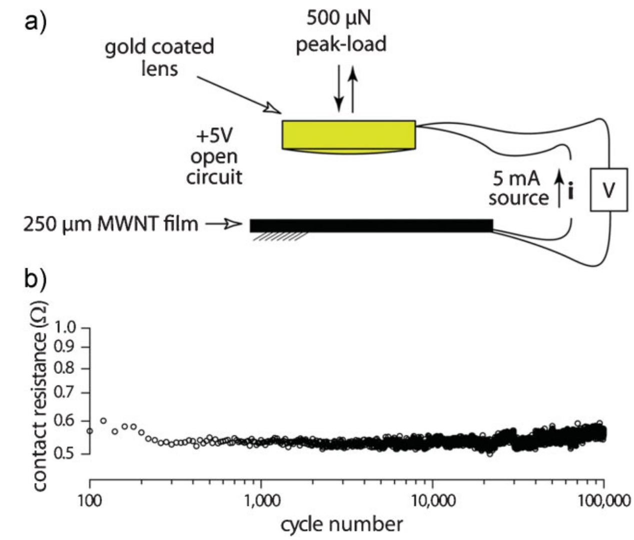

Figure 4. Reliability test with a point contact setup. a) Schematic of the experimental setup showing the 4-point probe measurement and arrangement of the voltage and current source. b) Contact resistance over 100 000 cycles is shown to be below 1 Ohm and steady for the entire experiment, which was run in open air over 4 days.

nanotube forests make stable, light and close electrical contacts at moving interfaces and result in considerably less noise as compared to the commercial electric brushes used in ordinary electric motors. As the nanotube contacts combine the simplicity and robustness of ordinary brushes and the excellent low-noise performance of brushless contacts one can see a significant potential of practical exploitation of such structures in all motors.

Experimental

CNT Growth and Electrical Brush Fabrication: Aligned MWCNT films are grown on patterned Si/SiO_2 templates (thermal oxide, 10 mm × 10 mm size and thickness of ~1 μm) by CCVD in a single zone tube furnace. The general process scheme is as follows: the inlet and outlet ends of the quartz tube are connected to the feeding and exhaust pipelines, next the whole reactor is evacuated to a base pressure below 0.5 Torr (1 Torr = 133.3 Pa) and purged with argon, and then the furnace is heated to the reaction temperature (770 °C). A small amount of precursor (1 mL solution of 20 g ferrocene in 1 000 mL xylene) is injected into the evaporator column preheated to 185 °C, then the valve between the evaporator column and the reactor is opened and the vapor is introduced into the quartz tube with a 30 mL/min flow rate of argon gas. After the pre-feeding step, the precursor flow rate is adjusted to 0.1 mL/min and maintained until the end of the process. CNT films detached from the substrate in EtOH:HF (7:3) solution were rinsed in ethanol and dried before sputtering of ~50 nm Cr and ~2 μm Cu on one side of the samples. Structures of 1.8 mm × 1.8 mm blocks were cut from the freestanding films by laser-assisted surface ablation using a defocused (~800 μm offset, spot diameter in the focal plane of ~15 μm) 3ω Nd:YVO_4 pulsed laser (pulse duration of 20 ns, repetition rate of 90 kHz, average power of 300 mW and scan rate of 50 mm · s^{-1} with multiple scans). The as-obtained MWCNT brushes were then soldered at 170 °C onto a flexible brass cantilever with ~10 μm thick layer of low melting point eutectic 46Bi–34Sn–20Pb solder paste (T_m = 96 °C).

Electrical Characterization of the Nanotube Brushes: *I–V* measurements were performed with a Keithley 6221 AC and DC current source combined with a Keithley 2182A Nanovoltmeter. Custom-made Labview code was used for controlling devices and acquiring measurement data. Pulsed ramp sweep was used to reduce power while performing sweep and minimizing heating of samples, which can skew the test results. A 3-point delta measurement takes one measurement before each pulse, one during each pulse, and one after each pulse. With this procedure thermoelectric EMF and moving offsets are cancelled out, leaving the true value of the voltage. In other words, pulsed measurement is relative measurement and reduces power, thus making more precise measurements. Noise measurements were carried out with a current-stabilized source (10 mA, Keithley 6221) and the bias voltage was measured as function of time with an oscilloscope (Agilent 53622A). The obtained data were processed with OriginPro 8 SR1's built-in fast Fourier transform (FFT) analysis tool.

AC Measurements: To use CNT brushes in an effective manner as rotating/sliding electrical contacts in electric devices, the films should either be directly grown on a conductive metal lead or alternatively be mounted on it, e.g., by soldering. In this work, we focus on soldered CNT brushes on metal bases. The effect of solderable metallic layers (2 μm Cu with ~50 nm Cr adhesive layer) on AC/DC electrical conductivity is investigated and compared with bare CNT brushes. DC electrical measurements were performed on each sample being fixed between slightly compressed gold plate contacts (Supporting Information, Fig. S2a). The linear *I-V* characteristics (with current sweep) show ideal Ohmic behavior for both types of samples, i.e., the sputtered metal layers have an insignificant effect on the DC electrical properties of the nanotube brushes. The resistance values are similar to each other (~1 Ω) indicating that the nanotubes of each brush contribute to the conduction in the same manner. AC impedance Z(f) measurements with frequency sweeps up to 2 GHz were carried out using an RF impedance/material analyzer (Agilent E4991A) equipped with a parallel-electrode surface mounted device (SMD) test fixture (Supporting Information, Fig. S2c). CNT brushes with sputtered Cr/Cu layers behave as a typical low-value resistor and show a small-series lead inductance at high frequencies (Supporting Information, Fig. S2b), albeit with a slightly lower inductance value ($L_{CNT/Cr/Cu}$ ~4.8 pH) and an additional small stray capacitance ($C_{CNT/Cr/Cu}$ ~1.2 pF) than that for the reference resistor component (L_{ref_R} ~5.7 pH); these values were calculated from the fitting parameters (see Supporting Information, Table S1) of the series *RL* impedance $Z(\omega) = R_L + j\omega L$ (for the reference resistor), and parallel *RL-RC* impedance $Z(\omega) = \frac{(R_l + j\omega L)(R_C - j/(\omega C))}{(R_L + R_C) + j(\omega L - 1/(\omega C))}$ (for the nanotube samples), where R_L is the corresponding low-frequency series resistance, R_C the parallel resistance, C the parallel capacitance, and $\omega = 2\pi f$. For bare CNT brushes at low frequencies, the resistive component is an order of magnitude higher (R_0 ~11 Ω) than that for the metal-coated CNT blocks suggesting a poor contact of the specimen with the small needlelike electrode of the test fixture (see Supporting Information, Fig. S2c inset), i.e., not all of the nanotubes in the brush are taking part in the conduction process. At higher frequencies, the impedance decreases indicating a capacitive component in the measured film, which seems to support the previous assumption concerning the non-optimal contact in the fixture. As high-frequency current is applied through the CNT network, an oscillating electric field appears between the poorly or not-contacted nanotubes and the well-contacted conductive parts. This results in a displacement current, i.e., the nanotubes having different potential show a capacitive cross-talk. An apparent stray capacitance of C_{CNT} ~2.7 pF is obtained, which is higher than that of the nanotube film with sputtered metal contacts. It is worth pointing out that for high-frequency electrical applications, it is indeed important to integrate the nanotube brushes with a solid conductive interface to minimize capacitive coupling in the nanotube layer, i.e., a reliable contact along the whole cross section of the aligned nanotube array block is essential. The sputtered copper layer applied here seems to fulfill this condition perfectly, and in addition, provides a surface that is easy to solder thus enabling a comfortable platform for fixing nanotube brushes in the electromechanical system.

Mechanical Investigation of MWCNT Films: Dynamic effective Young's modulus of freely moving vertically aligned carbon nanotube forest was determined by measuring their frequency response under constant 10 μm displacement. The forest was vibrated by piezoelectric actuator and uniaxial displacement of the nanotube bundles was measured by fibre-optic laser vibrometer OFV-5000 (Polytec GmbH, Germany). The displacement difference between the nanotubes and the actuator showed the first resonance (f_r) at 1060 Hz (see Supporting Information Fig. S3) exhibiting a Q factor of 13.2 and a corresponding vibrational damping loss factor η of 0.076, determined by $\tan\delta = Q^{-1} = \Delta f/f_r$ for low to moderate loss materials ($\tan \leq 0.1$) where f_r is resonance frequency and Δf is frequency bandwidth between points $1/\sqrt{2}$ from magnitude of the resonance. Calculated from dimensions and density of 0.3 g/cm^3 nanotube forest obtained dynamic Young's modulus of $\sim$2.4 MPa under uniaxial $\sim$1% compression. Soft materials like neoprene rubber ($E \sim 7.5$ MPa, $\tan\delta \sim 0.89$) typically display a high loss modulus, i.e., mechanical loss tangent, while nanotube bundles are fairly easy to bend and buckle but introduce relatively low loss in comparison to internal friction of cross-linked elastomer. More efficient damping can for example be introduced by composite structures of carbon nanotubes and polymers inhibiting vibrations more effectively [21]. In addition to very soft material, nanotubes offer a vast amount of contact points as the fiber density of nanotubes can be $\sim 10^8$/mm^2 (see [12]) whereas carbon fiber brushes exhibit a fiber density of $\sim$2 300/mm^2. Two fundamental detriments that impact on the practicability of the fiber brushes are commutation mechanical chopping by the commutator bar edge, which introduces higher wear rate and fiber breakage, and arching at trailing edge generating rapid erosion of the brush. In theory, decreased diameter of the fiber will diminish the above mentioned problems [22]. Cantilevers were assembled along the sliding direction, as shown in Figure 1b and 1c, thus providing stiff support for the brushes for tangential forces but also flexibility in the normal direction of the axle.

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