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Recovery torque modeling of carbon fiber reinforced shape memory polymer nanocomposites

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Carbon fiber and carbon nanofiber paper (CF&CNFP) can be incorporated into shape memory polymers (SMPs) to increase electrical conductivity and allow high speed electrical actuation with a low power. This paper studies the interactions among the recovery torques of CF&CNFP and SMP and the gravity torque during the shape recovery process. The proposed recovery torque model in a SMP CF&CNFP based structure is validated by experimental data obtained using a recently developed low cost, non-contact measurement testbed. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4829937>]

Shape memory polymers (SMPs) are smart materials that can memorize permanent shapes and recover to them under external stimulus such as light, heat, and electric power.^{1,2} Being capable of recovering large strains, SMP materials have great potential to be used in many emerging applications such as deployable structures, textile, surface decoration, and biomedical devices.^{3,4}

To date, SMP materials are only capable of memorizing a limited number of shapes.¹ These shapes are not flexible after they were manufactured. Thus, it is desirable if SMP materials can be controlled precisely to intermediate shapes in a convenient and cost effective approach. To achieve precision controls of the shape recovery process, a model that can predict the recovery torque is necessary. Much attention has been brought to the development of constitutive models⁴⁻⁸ relating strain and stress for thermal-driven, water-driven, or light-driven SMPs.⁹ Also, research has been conducted to enhance the mechanical properties of SMPs.¹⁰ However, high computational cost, unknown and possibly changing material properties, and simplification assumptions used in deriving these constitutive models make them less attractive from the practical perspective of real-time shape recovery controls.

The SMP sample studied here was manufactured through the following steps. The 500 μm thickness carbon nanofiber paper (CNFP) was made by the infiltration method. The carbon nanofibers (CFs) were dissolved into 400 ml deionized water and then sonicated using a high intensive probe sonicator (1000 W) for 30 min in a 1 l beaker. In order to disperse CFs evenly, 4 ml of surfactant Triton- $\times$ 100 was added into the solution. Then, the solution was sonicated for another 30 min and cooled down to the room temperature. After that, the as-prepared suspensions were sonicated for 2 min and immediately transferred into the filtration system. The CNFP was fabricated by filtration method. After the CNFP was fabricated, an autoclave was used to make fiber reinforced SMP nanocomposites. The resin used is the

polyurethane based SMP (MP5510), which is provided by SMP Technologies, Inc., in Japan. SMP resin part A and part B were dried at 50 °C under a -27 inHg vacuum atmosphere for 3 h. Part A and part B were mixed for 2 min at 60 rpm and then poured into a die, which was dried for more than 3 h at 70 °C. The vacuum bag tooling was closed and the -27 inHg vacuum is applied immediately. A 15 psi pressure was applied for 5 min then increased up to 50 psi. The temperature increased to 75 °C after 5 min. The curing process ended after 3 h.

The structure of manufactured SMP CF&CNFP is composed of three layers (Fig. 1): (i) CNFP (very thin and enables the electrical actuation); (ii) CF (improves mechanical properties such as strength and modulus); and (iii) SMP matrix.

When above the glass transient temperature and at low deformation levels, SMPs exhibit a fully recoverable linear elastic behavior.¹¹ The recovery torque is modeled using the Hooke's law¹² as $\tau_s = k_s(\theta_s - \theta)$, in which θ_s and θ are the permanent and current deflection angles, and $k_s > 0$ is the spring coefficient. Compared to the CF layer, the CNFP layer is thin and soft, the contribution of which to the recovery torque is relatively low. Thus, the recovery torques of CF and CNFP are treated together as $\tau_c = k_c(\theta_c - \theta)$, where θ_c and $k_c > 0$ are the neutral point and spring coefficient. The recovery process (Fig. 2) is governed by

FIG. 1. Three layered SMP CF&CNFP structure.

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$$I\dot{\omega} = \tau_s + \tau_c - mgl \cos \theta, \quad (1)$$

where I , ω , m , g , and l are the moment of inertia, angular velocity, mass, gravitational coefficient, and torque arm. The overall recovery torque $\tau_T = \tau_s + \tau_c$ of SMP CF&CNFP can be calculated using $\tau_T = I\dot{\omega} + mgl \cos \theta$. There is an equilibrium point θ_N in Eq. (1): when $\theta = \theta_N$, the resultant torque is zero and $\dot{\omega} = 0$.

A low cost tested (Fig. 3) is developed to measure dynamic behaviors of CF&CNFP in recovery. Two Microsoft LifeCam[®] webcams (resolution: 1920×1080 , frame rate: 30/s, and field of view: 75°) are used to monitor geometry information. Image processing software is programmed to calibrate the cameras (obtaining the intrinsic and extrinsic parameters), detect the color dots painted on the material surface, reconstruct the 3D coordinates of these dots, and calculate the deflection angle in real-time. The working frequency is 2 Hz. The angular velocity and angular acceleration of the structure are calculated using the deflection angle through the five-point stencil method.¹³ The MLX90614 infrared thermometer[®] (resolution: 0.02°C and accuracy: 0.5°C) measures the temperature near the axis where the material is rotating about. It is worth noting that the recorded temperature is not on the surface of the material, instead it is about 7 mm below the material surface (in the vertical direction) and 16 mm relative to the rotation axis (in the horizontal direction). Therefore, the temperature recorded is below the actual material surface temperature. An ASC712 current sensor[®] (sensitivity: 185 mV/A) measures the current going through the material.

In each experiment, the material is first bended to 0° when its temperature is above the glass temperature, and then cooled down. After that, a constant voltage is applied to heat the material until the material is deflected to its permanent shape. The material is not loaded in its recovery.

After removing experiment outliners, the following 33 recovery processes are recorded: 7 cases for 20 V and 30 V and 4 cases for 15 V, 17.5 V, 22.5 V, and 25 V. The averaged deflection angular velocity and deflection angle profiles for all these cases are shown in Fig. 4: (i) When the recovery starts and the deflection angle $\theta < \theta_N$, the recovery torques from SMP and CF&CNFP are positive but decreasing. Since the recovery torque magnitude drops in a quicker fashion than that of the gravity torque, the overall angular acceleration $\dot{\omega}$ decreases but still maintains positive. (ii) When $\theta = \theta_N$, the recovery torque of SMP is positive. The resultant torque is zero, the angular acceleration is zero, and the angular velocity reaches its maximum value. The maximum angular velocities for different experiments all happen around 60° (Fig. 4), which means that the equilibrium point

FIG. 2. Free body diagram in the recovery process.

(1) Software (2) Power Supply (3) Power Control Circuit (below the platform) (4) Temperature Sensor (5) SMP CF & CNFP (6) Webcams

FIG. 3. Non-contact dynamic torque measurement testbed.

θ_N is largely affected by the strain instead of how quick the energy is injected into the nanocomposite structure. (iii) When $\theta_N < \theta < \pi/2$, the recovery torque of SMP keeps decreasing but still positive. The gravity torque decreases to zero. The recovery torque of CF&CNFP may decrease (in the positive direction) or increase (in the negative direction), but the resultant torque starts to increase in the negative direction. (iv) When $\pi/2 < \theta < \theta_\infty$, the gravity torque increases in the positive direction, and the recovery torque of SMP decreases but is still in the positive direction. However, the recovery torque of CF&CNFP increases in the negative direction, which results in a net decrease in the magnitude of the negative angular velocity (Fig. 4).

The spring coefficient of SMP is almost constant when the material temperature is 15°C above or below the glass temperature.¹⁴ In the glass transient stage, it can be modeled as the following exponential function:¹⁴

$$k_s = k_{s,0} \exp\{c_1[T_G/(c_2T) - 1]\}, \quad k_{s,0} > 0. \quad (2)$$

The mechanical property of CF&CNFP is stable and thus k_c is assumed to be constant.¹⁵

The nonlinear constrained optimization solver in MATLAB (fmincon) is used to identify the coefficients in the proposed model (Eq. (2)). For our 33 experiment scenarios, $\theta_s = 150^\circ$ is assumed. The objective function to be minimized is

$$J = \sum_{k=1}^N \frac{|I\dot{\omega}_k + mgl \cos \theta_k - k_s(\theta_s - \theta_k) - k_c(\theta_c - \theta_k)|}{|I\dot{\omega}_k + mgl \cos \theta_k|}, \quad (3)$$

FIG. 4. Averaged deflection angle and angular velocity.

FIG. 5. Identified equilibrium point and coefficients in the proposed torque model for different voltage inputs.

FIG. 6. Recovery torques of SMP CF&CNFP.

where N is the number of measurements in each case, and subscript k denotes the k^{th} experiment data. As mentioned in Ref. 14 and validated here, both constant and exponential spring coefficient cases are tried in the parametric identification. The constraint bounds of spring coefficients are carefully tuned such that the identified parameters are consistent, and the residuals in the performance index are minimized and consistent for all 33 cases.

The following arguments can be made about the parametric identification results. (i) The residuals for all 33 experiments are small in both the constant and exponential spring coefficient cases (between 4.32% and 6.78%). (ii) In Fig. 5(a), the equilibrium point θ_N is consistent within a range of $[59^\circ, 61^\circ]$. (iii) The spring coefficients of recovery torques are consistent (Figs. 5(b) and 5(c)). (iv) The identified c_1 in Eq. (2) is almost zero (10^{-16}), which validates the observation in Ref. 11 that the mechanical properties of SMP are nearly constant when the temperature is above the glass transition region. (v) Figure 6 shows one identified result that matches well with the experimental data. The temperature value in the x-axis is the temperature of the point about 7 mm below the material surface (in the vertical direction) and 16 mm relative to the rotation axis.

The reasons that the identified data do not perfectly match the experimental data include: (i) the accuracy of vision, temperature, and current sensors is not high enough; (ii) the mechanical-thermal-electrical properties of SMP CF&CNFP may degrade along with repeated experiments;

and (iii) the mass, moment of inertia, and length are not perfectly measured.

Although the identified model is not 100% accurate, it can help (i) researchers in material processing and synthesis to predict the strength of recovery torques and how they are interacting between each other; (ii) control engineers to design robust/adaptive controllers to drive precisely not only the SMP CF&CNFP deflection angle but also the morphing speed.

Two major contributions of this letter are summarized here. First, a low cost, non-contact testbed is developed to measure dynamic recovery torque, geometry, electrical, and temperature information in SMP nanocomposites recovery process. Second, a recovery torque model is proposed and validated by experimental data. As shown in Ref. 14 and validated by the parameters' identification, the spring coefficient of CF&CNFP is assumed either to be an exponential function or constant depending on whether it is inside of the glass transition period or not. It is found that there is an equilibrium point where three torques are balanced. The proposed model can be used in controller designs to achieve precision shape recovery processes, as well as guide the SMP nanocomposites material processing to achieve a desired recovery dynamic response.

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