Heat Machine Based on Differential Helical-Elastic Thermal Actuator with Mechanisms to Determine Degradation

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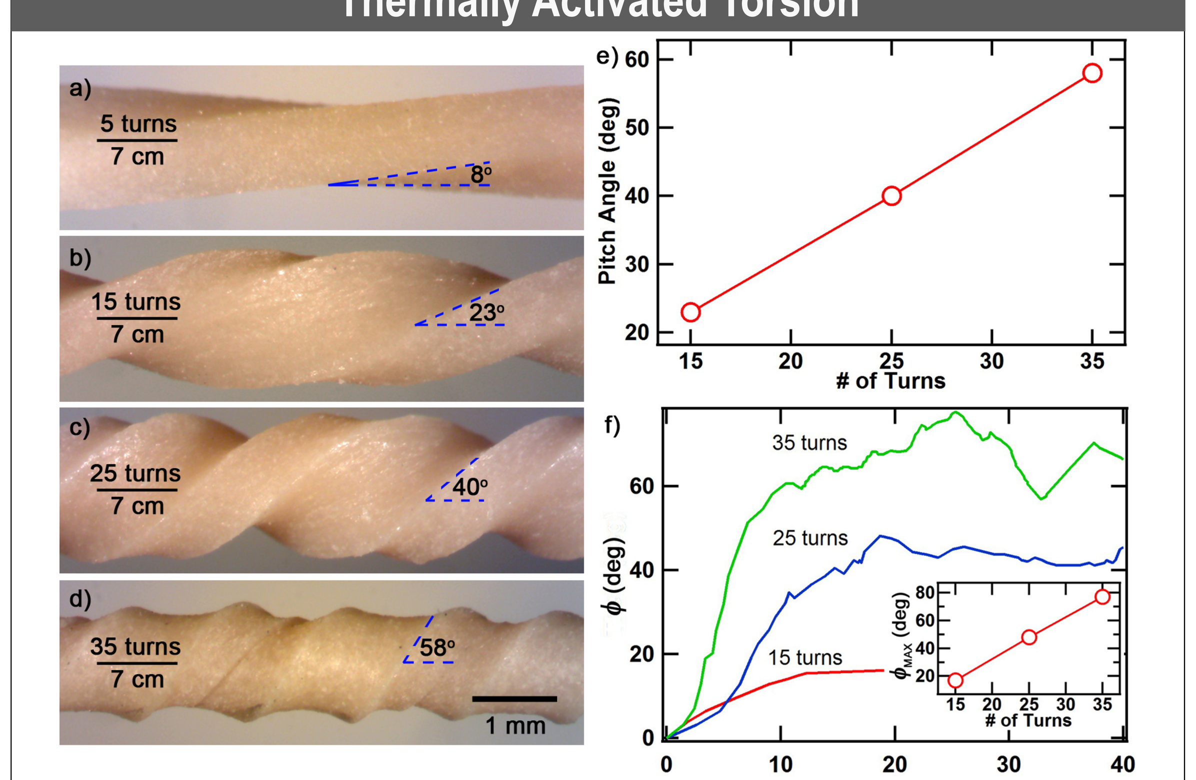
Abstract

We describe a simple heat machine that operates on the torsional degrees of freedom in a stretched, helical (twisted) elastic band. When one half of the band is heated or cooled, the central region undergoes a rotation to maintain equilibrium in both tension and torsion, and the rotation is detected by a gear attached at the midpoint. The effect can be explained based on the negative thermal expansion of the elastic material and the resulting change in the elastic spring constant. This produces a modification in the helical pitch to maintain a uniform torsion and tension in the structure. As degradation was present in the elastic band at a certain point, it was necessary to monitor stress and strain rates of the actuator to monitor its efficiency. As there is no way of doing this while the device is operating, we also present means of detecting degradation in the elastic band due to heat exposure.

Introduction

This work was motivated by a recent report by Lima et al. [1] who have shown that wax-filled twisted carbon nanotube yarns can exhibit an unusually large azimuthal displacement along the axis of tension when heated. Our main purpose in this report is to show that a similar effect is evident in a conventional rubber band geometry where the mechanism can be understood by a simple mechanical model. Rubber has the unique characteristic of contracting when heated. This is due to a change in entropy from low to high which changes the atomic structure originally from order to tangled coils. Utilizing this property, a proof-of-concept heat machine array based on rubber bands is demonstrated for mirror positioning and for lifting weights. Mathematical models are derived to quantify the properties of the heat machine. Finally, we report the acoustic, luminosity, and hydrophobic properties of degraded rubber for monitoring potential mechanical failure of the heat machine.

Thermally Activated Torsion



Thermally activated torsion results from a temperature induced tightening effect. A larger rotation is observed by increasing the temperature or the number of twists. At higher temperatures, the elastic band is prone to degradation, reducing the reversibility of the torsion.

Tensile Properties

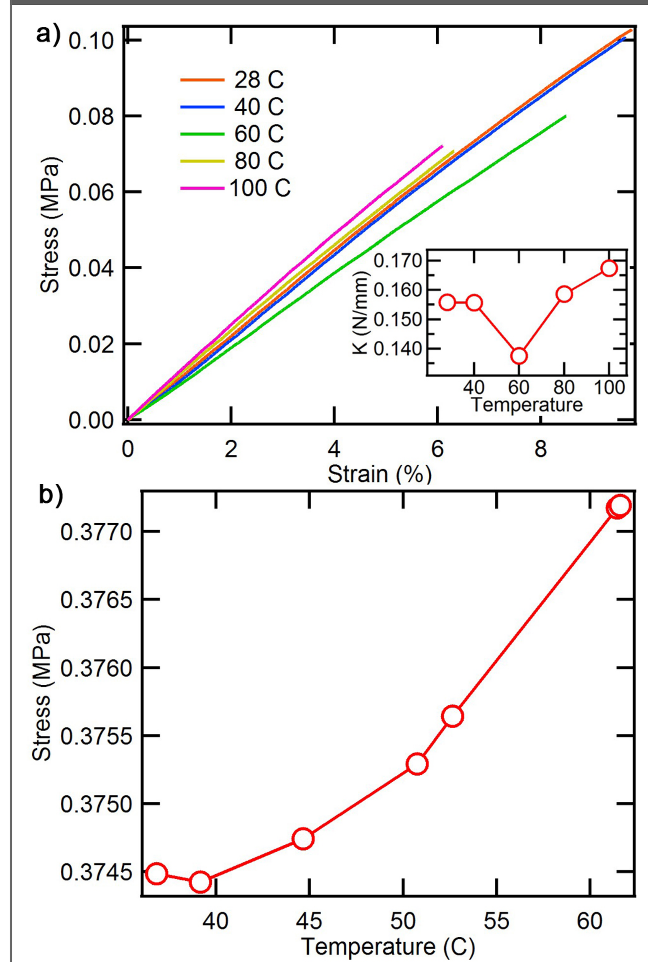


Figure a) suggests that heating the rubber band decreases its spring constant up to 60 degrees Celsius. Beyond this temperature, the spring constant value is higher than its original room temperature value.

Figure b) suggests that the higher the temperature applied to an elastic band, the more a tightening effect is exhibited and impacts the system.

Mathematical Model

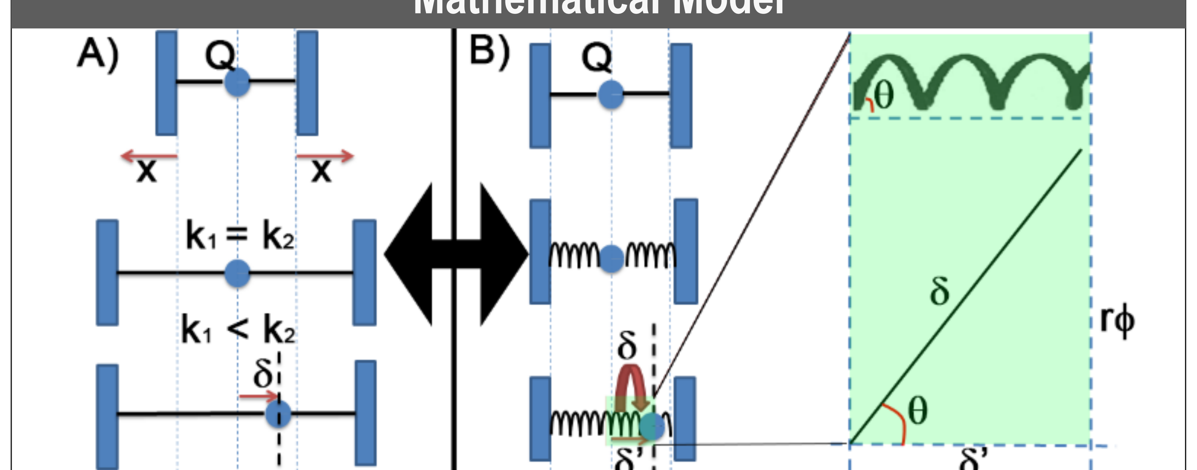


Figure A) Un-twisted

$$F_1 = k_1(x+\delta) = k_2(x-\delta)$$

$$\delta = \frac{k_2 - k_1}{k_1 + k_2}x$$

Q is the initial position at equilibrium.
δ Is the displacement from the equilibrium position.

Figure B) Twisted

$$\int d\vec{s} = \int r d\vec{\phi} + \int d\vec{x}$$

$$\vec{s} = \int rP dx\hat{\phi} + \int d\vec{x}$$

$$\vec{s} = rPx\hat{\phi} + \vec{x}$$

$$s = \sqrt{r^2P^2x^2 + x^2} = x\sqrt{r^2P^2+1}$$

Twisting is equivalent to stretching.
ϕ is the azimuthal rotation.
Pitch, P, is the change in ϕ with respect to x.

How Pitch Effects Number of Turns and Displacement from Equilibrium Position

$$\delta^2 = (\phi r)^2 + \delta'^2$$

$$\delta^2 = (\phi r)^2 + \frac{\phi^2}{P^2}$$

$$\delta^2 = \phi^2\left(\frac{r^2P^2+1}{P^2}\right)$$

$$\phi = \sqrt{\frac{\delta^2 P^2}{r^2P^2+1}}$$

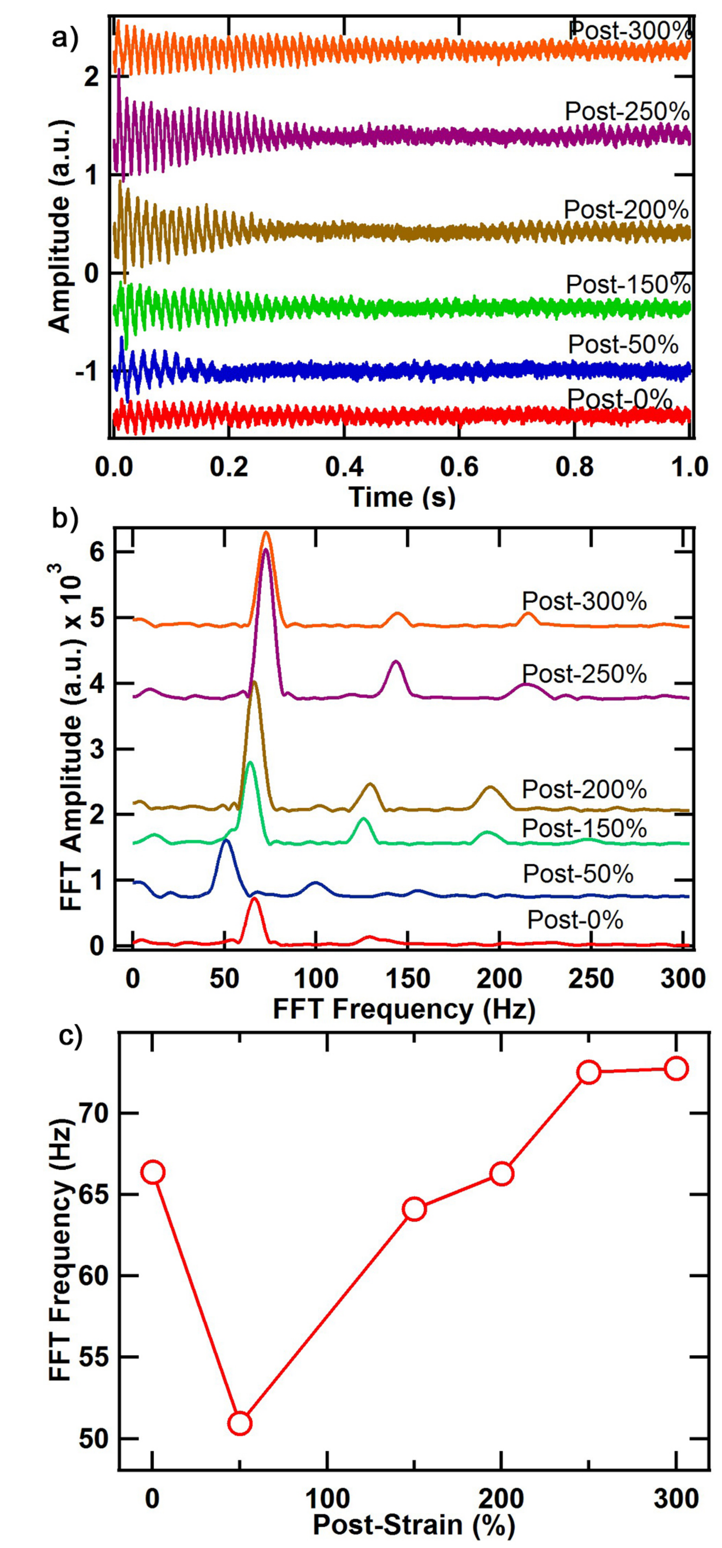
$$\phi \simeq \delta P, \quad \text{If } P \ll 1$$

$$\phi \simeq \frac{\delta}{r}, \quad \text{If } P \gg 1$$

$$\theta = \arctan\frac{r\phi}{\delta'}$$

δ is the total displacement of point Q around the radius of the spiral.
δ' is the displacement of point Q in the x-direction.

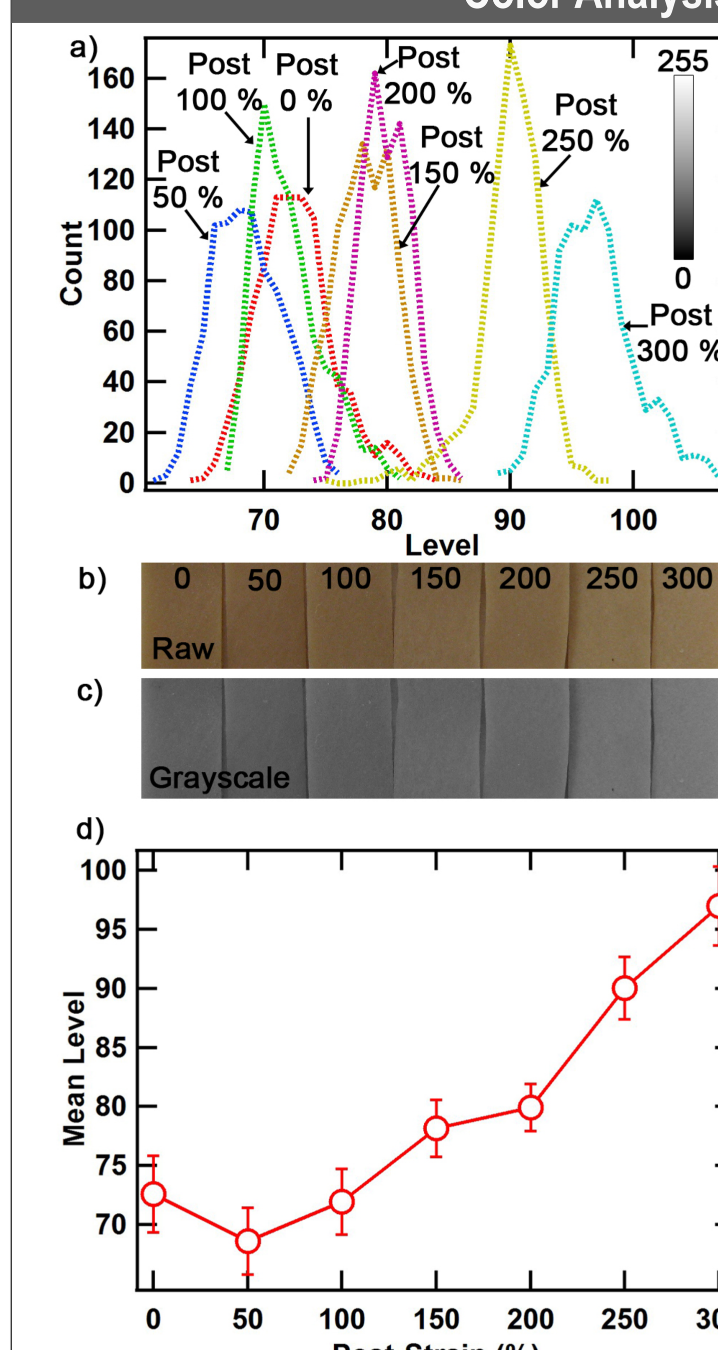
Sound Analysis



In an effort to indirectly test for mechanical degradation, monitoring accoustic properties may be useful. Excluding the 50% post-strain, sound frequencies increase with strain. This indicates that post-strained rubber bands are losing their flexibility as a result of strain that is beyond the band's elastic limits.

(a) Monitoring of sound amplitude over time. Curves have been shifted for clarity. (b) Fast-Fourier-Transform (FFT) analysis of the sound waves showing the first, second, and third harmonics. (c) Post-strain dependent frequencies

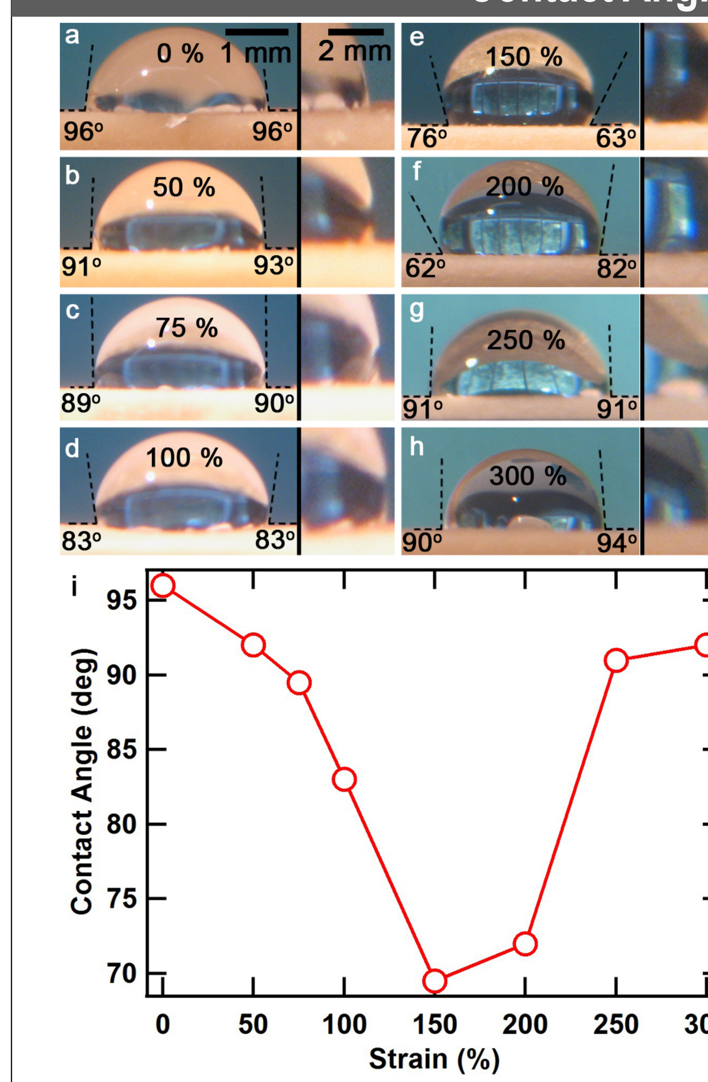
Color Analysis



A systematic increase can be observed in brightness, excluding the 50% post-strain which decreases.

Brightness profile of single strand rubber-bands after being strained (post-strained). (a) Brightness spectra of the post-strained rubber-bands. The bar indicates the grayscale levels with 0 and 255 being the less and most bright, respectively. (b) Raw and (c) the corresponding grayscale photographs use in the analysis. (d) Average level vs. post-strain curve relating brightness with amount of mechanical degradation

Contact Angle



It can be observed that the rubber becomes more hydrophobic as the strain increases up to a certain point, at which time the rubber becomes dramatically more hydrophilic. The inconsistencies of the contact angle at 150% and 200% strain can be attributed to the rubber becoming highly hydrophobic, thus making the water droplet more unstable as more area is concentrated at the top the droplet. Beyond this point, the material itself is beginning to break down as micro-tears become prevalent.

Conclusion and Future Work

We have recorded the tensile properties of natural rubber under various temperatures and strains in the hopes of building a reversible actuator. The rubber used in this study has a high affinity for degradation. As there is a breakdown point, we have explored ways of analyzing color saturation, sound frequency, and hydrophobicity to indirectly determine the reliability of such an actuator. In general, highly degraded rubber produced a higher frequency sound and brightness. In regards to hydrophobicity, we find that rubber initially becomes more hydrophobic when stretched before becoming hydrophilic. In principle, by observing the sound, color, and affinity to water of our device, it is possible to anticipate mechanical failure. We have derived mathematical models depicting the linearly proportional relationship of degree of rotations and pitch counts of our actuator. By experimenting with different composites of rubber, the performance of our actuator can be improved in principle. Furthermore, our prototype can easily be scaled up to achieve a stronger actuator by combining many rubber bands. Our experiment suggests that a device such as a thermally activated optical mirror may be practical.

Acknowledgements

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References

[1] M. D. Lima, et. al. *Electrically, Chemically, and Photonically Powered Torsional and Tensile Actuation of Hybrid Carbon Nanotube Yarn Muscles*, Science **338,** 928-932 (2012).