Bending Artificial Muscle from Nylon Filaments

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ABSTRACT

Highly oriented nylon and polyethylene fibers shrink in length and expand in diameter when heated. Using this property, in this work, for the first time we are introducing a type of bending artificial muscle from nylon filaments such as fishing line. Reversible radius of curvature of 0.23 mm^{-1} was achieved with maximum reversible bending amplitude of 115 mm for the nylon bending actuator. Peak force of up to 2040 mN was measured with a catch-state force of up to 40% of the active force. A 3 dB roll-off frequency of around 0.7 Hz was observed in the frequency response of the bending actuator in water.

Keywords: artificial muscles; nylon; bending actuators; fishing line; bending artificial muscle.

1. INTRODUCTION AND BACKGROUND

Highly oriented Nylon and polyethylene exhibit anisotropic negative thermal expansion coefficients [1],[2]. Nylon 6,6 fishing line, with its polymer chains orientated along its length, has a thermal expansion coefficient of -3% which can be amplified to 49% by twisting and coiling [1].

Dry bending actuators are usually made by attaching two materials with linear expansion/contraction abilities. By actuating one of the materials at a time, bending can be achieved. The same concept can be used for polymer or carbon nanotube based actuators in which by inserting large ions into one side bending can be achieved [3,4]. Shape memory alloy, piezoelectric bimorph bending actuators, ionic polymer metal composite (IPMC) bending actuators are some examples of existing technologies. However, there are some challenges that limit application of these actuators in different devices. For example, aside from having high manufacturing cost, shape memory alloys suffer from having short life cycle. Also the hysteresis in their actuation mechanism makes precise control over their output parameters (i.e. displacement/force) very difficult. In contrast, nylon costs around $5/kg, has a relatively high life cycle (as a thermal linear actuator [1]) and is hysteresis-free [1]. Therefore, it can be a good candidate for application in linear artificial muscles.

In this work for the first time we are demonstrating use of a nylon beam (fabricated by roller-pressing a fishing line) in the design of a bending thermal actuator. A Joule heating element such as silver paint or nichrome wire is added to both sides of the nylon beam. It is common to use metallic nanowire yarns [5] or carbon nanotube yarns [1] as the Joule heating

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element in the design of thermal actuators, but as we have shown previously, silver painting is a very simple and relatively cheap technique for making the Joule heating element for artificial muscle [2]. By passing current through the Joule heating element of one side of the nylon beam at a time, that surface contracts and causes bending of the actuator.

2. METHODS

The bending actuator was fabricated by first performing heat treatment on a nylon 6,6 monofilament such as nylon fishing line (Sufix Superior, 1.40 mm) at 90 ˚C for 45 min. This process is necessary to remove any deformation in the filament and to make it as straight as possible. The filament with original circular cross-sectional area was then flattened slightly by a roller press (Figure 1A) to form nylon beams. After cleaning the nylon beams with ethyl alcohol, a Joule heating element such as silver paint (SPI®, flash dry) or nichrome wire (75 µm in dimeter) was added to both sides of the filament (Figure 1B, C). It is important to ensure that at this stage both sides of the beam are electrically isolated. Finally, a piece of very compliant copper wire was slightly wrapped around the tip of the beam to make electrical connection to the actuator. To ensure good electrical connection between the copper wire and the two sides of the beam, small amount of silver paint was added at the end.

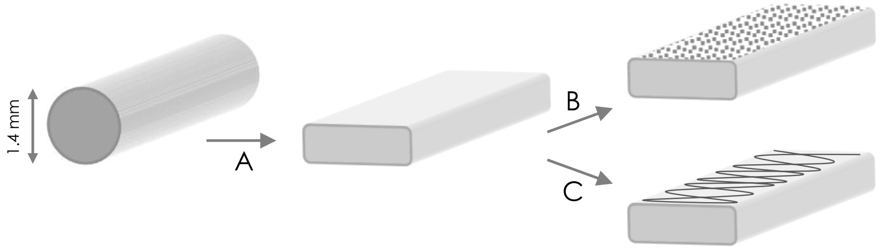

Figure 1 - (A) A Nylon beam is formed by roller-pressing a nylon filament. After cleaning the beam with ethyl alcohol a Joule heating element is added to the top and bottom surfaces of the beam. The Joule heating element can be either in form of a silver paint compound (B) or nichrome wire in double zigzag configuration (C).

In order to measure the force exerted by the actuator, one 4.5 N load cell (Futek) was used with a signal conditioning amplifier (Vishay 2311). All the data were then acquired by a high bandwidth data acquisition system (Bio-logics VMP2). Frequency response of the actuator (in DI water) was measured by performing imaging analysis. Finally, thermal measurement at the body surface of the actuator was performed by attaching four fast response micro thermistors (Alpha Techniques 2A1002-C3) with thermally conductive adhesive (Arctic Alumina Thermal Adhesive) to both sides of the actuator (Figure 6B). Resistance value of each thermistor was calculated by reading the voltage drop across a 4.4 kΩ precision resistor in series with it. In order to accurately calculate values of the temperature from thermistors' resistance values, a mathematical model was derived and implemented in MATLAB.

3. RESULTS AND DISCUSSION

With the nylon bending actuators, we achieved a radius of curvature around 0.56 mm^{-1} in an irreversible actuation (Figure 2A) and 0.23 mm^{-1} in a reversible actuation (Figure 2B,C). Maximum reversible amplitude of about 110 mm is achieved for a sample with length of 115 mm, thickness of 1 mm, and width of 1.8 mm. This bending actuator can be modeled as a two-resistor network in which only one resistor will be activated at a time (Figure 2D). To achieve a fully symmetric displacement, the resistance of the Joule heating element on both sides should be as close as possible, otherwise drift in the displacement will be developed over time. Silver paint coating offered a linear resistance of 150 $\Omega\cdot m^{-1}$ while the nichrome wire offered a linear resistance of 2.4 $k\Omega\cdot m^{-1}$ over the length the wire and 146 $\Omega\cdot m^{-1}$ per length of the nylon beam (in a double-zigzag configuration).

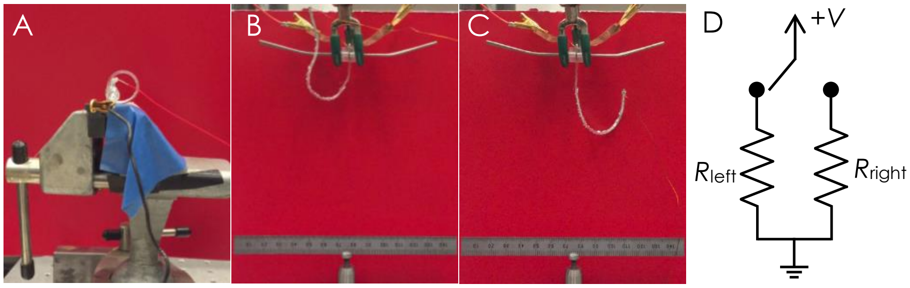

Figure 2 – (A) The nylon curled over two times which results in radius of curvature around 0.56 mm^{-1}. (B) and (C) show radius of curvature around 0.23 mm^{-1} for a reversible actuation.

Maximum peak force of 2040 mN is measured from a single nylon beam (with length of 43 mm, width of 1.8 mm, and thickness of 1 mm) at a step input voltage of 4 V (Figure 3A). The 2040 mN peak force is 50 times higher than the value reported for ionic-liquid-based bucky gel (40 mN)[6], almost 1000 times higher than the force generated by the trilayer polypyrrole bending actuators, and almost 100 times higher than the blocking force that can be generated by the IPMC-based bending actuators [7]. This force can be scaled up by having more beams in parallel. The bending artificial muscles made by our proposed technique can have a “catch-state” or “lock-state” by slightly chemically treating the nylon filament. After chemical treatment, a free standing nylon beam can be bent to a desired angle without experiencing noticeable spring back. Figure 3B illustrates this catch-state behavior to a certain degree. After turning off the input power, the actuator still exerts force on the load cell which is almost 40% of the force generated in the active state (Figure 3B).

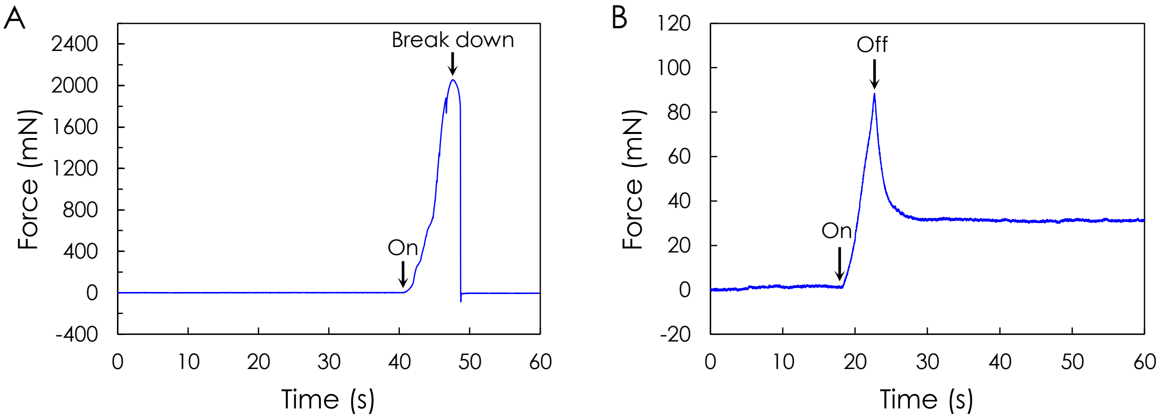

Figure 3 – (A) Peak force generated by the nylon bending actuator at input voltage of 4V. (B) Demonstration of the "locking-state" by applying a pulse to the nylon bending actuator.

Frequency response of a nylon bending artificial muscle (with length of 60 mm, width of 1.8 mm and thickness of 1 mm) was measured in DI water. The frequency response plot (Figure 4) shows 3 dB roll-off frequency of around 0.7 Hz. Since cooling time is a limiting factor in achieving fast and reversible actuation, the experiment for measuring the frequency response was performed in water. In air, at room temperature, the bandwidth for achieving a reversible actuation response is lower.

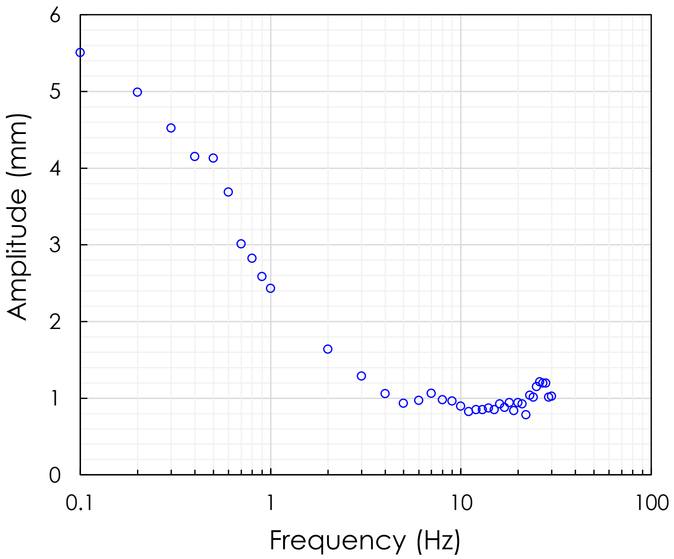

Figure 4 – Frequency response of a bending artificial muscle in DI water at room temperature. The 3 dB roll-off frequency is around 0.7 Hz.

The bending amplitude was measured to be a function of the applied potential. At 0.5 Hz the applied potential was increased from 1 V to 2.2 V in increments of 0.2 V for a sample (with length of 65 mm, width of 2 mm, and thickness of 1.2 mm) that was painted with silver on both sides. As Figure 5 suggests, the resistance of the silver coating changes slightly as a function of voltage. We speculate that since an emulsion of silver micro particles in an organic solvent is used in the silver paint, increasing the voltage, which leads to an increase the temperature, can cause complete drying of the paint and/or possibly change the packing density of the silver particles and thus change the resistance. Figure 5 shows a non-linear relationship between the applied voltage and the amplitude.

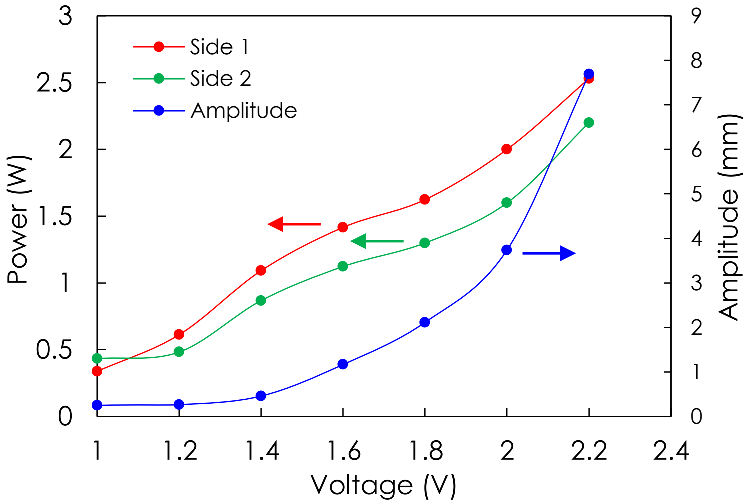

Figure 5 – Power vs applied potential and actuation amplitude as function of applied potential.

In the same experiment, we also measured the temperature at the silver paint surface on both sides of the actuator. Figure 6B shows the configuration of the sensors on the actuator. At 0.5 Hz, in air at room temperature, as we increased the voltage, the temperature on both sides of the actuator also increased (Figure 6A). Sensors 2,3, and 4 show very similar trend; however, sensor 1 shows a smaller change in the temperature. After performing the experiment, we observed that sensor 1 didn’t have a good thermal contact with the sample; however, it still illustrates the trend correctly. One of the important observations here is that the overall temperature increases as the voltage increases (Figure 6A,C), but since the applied voltage is alternating between the two sides faster than the cooling time constant of the beam, the thermal oscillation will grow as a function of voltage (Figure 6A). Figure 6D (small time window from Figure 6A) shows the values of temperature measured by sensor 3 (at applied potential of 2V). The peak-to-peak temperature (T_{pp}) change is about 2 °C. This small T_{pp} can be explained by the fact that nylon 6,6 has thermal conductivity of 0.25 $W \cdot m^{-1} \cdot K^{-1}$ which is very low compared to the thermal conductivity of silver (~ 420 $W \cdot m^{-1} \cdot K^{-1}$) and thus the actuator’s cooling rate is limited by the cooling time of the nylon beam itself. As Figure 6A shows, it takes about 180 s for the beam to reach the steady state value at room temperature. In other words, the actuator basically operates by T_{pp} (at its surface) of about 2 °C in elevated temperatures (> 60 °C).

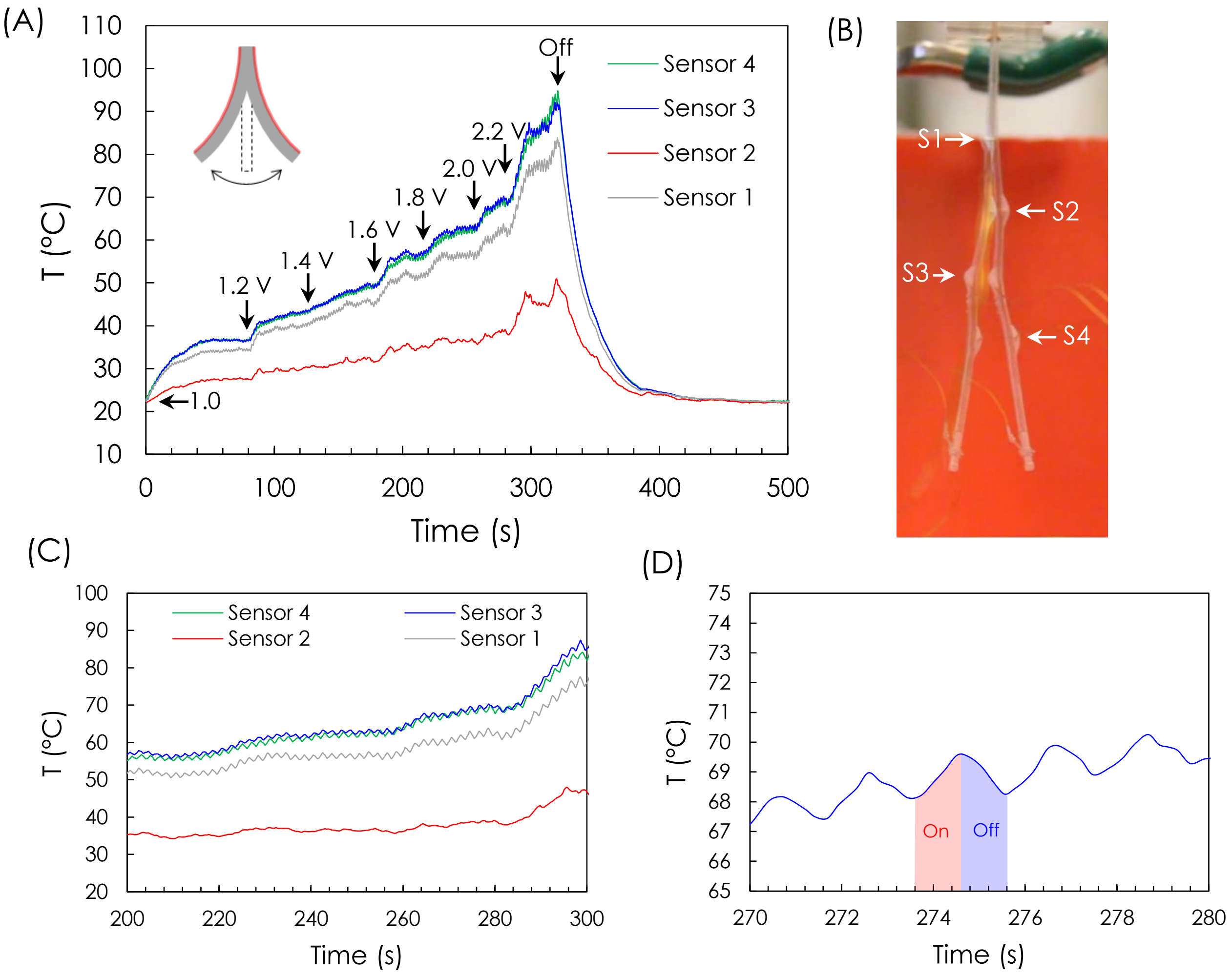

Figure 6 – (A) Temperature at the surface of a nylon bending actuator coated with silver paint was measured by four fast response micro thermistors. (B) The nylon bending actuator in action. S1, S2, S3, and S4 shows the micro thermistors attached to the sample by a thermally conductive adhesive. (C) A time slice of the results in part (A). (D) shows even more magnified version of the results from sensor 2 in part (C).

4. CONCLUSION

In conclusion, in this work we presented a simple technique for fabricating a bending artificial muscle using nylon fishing line. The nylon bending actuator could exert a force of around 2040 mN with 40% retention (i.e. catch-state). The nylon bending actuator's force capacity along with its ability to reversibly bend with a radius of curvature of 0.23 mm^{-1} make it a good candidate for application in biomedical devices. Aside from the performance, the simplicity of our proposed technique as well as the cost of the raw materials makes this actuator suitable for use in one-time-use biomedical tools and components.

5. ACKNOWLEDGMENT

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