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Development and Characterisation of a Multi-material 3D Printed Torsion Spring

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Abstract. *Compliant actuation methods are popular in robotics applications where interaction with complex and unpredictable environments and objects is required. There are a number of ways of achieving this, but one common method is Series Elastic Actuation (SEA). In a recent version of their Unified Snake robot, Choset et al. incorporated a Series Elastic Element (SEE) in the form of a rubber torsional spring. This paper explores the possibility of using multi-material 3D printing to produce similar SEEs. This approach would facilitate the fabrication and testing of different spring variants and minimise the assembly required. This approach is evaluated by characterizing the behavior of two printed SEEs with different dimensions. The springs exhibit predictable viscoelastic behavior that is well described by a five element Wiechert model. We find that individual springs behave predictably and that multiple copies of the same spring design exhibit good consistency.*

Keywords: Series Elastic Actuation, 3D Printing, Compliance

1 Introduction

Traditional robotic systems generally use stiff actuators, which have advantages such as increased precision and stability [1]. However there are situations where other factors have greater importance. Compliant actuators can increase shock tolerance [1], improve force control accuracy [2], simplify control systems [3] and improve safety [4]. There are a number of different approaches for achieving compliance, but one of the most common strategies is Series Elastic Actuation (SEA), in which a compliant elastic element (SEE) is connected in series with the actuator. This approach is used in the latest version of the Unified Snake robot developed by Choset et al [2]. Specifically, they developed a compact torsion spring consisting of a molded natural rubber element bonded between two machined metal plates. The rubber element has a tapered cross section designed to maintain uniform shear stress[5], as can be seen in Figure 1. Their manufacturing process is undoubtedly effective, but it is also quite complex. If a simpler process could achieve similar performance this would clearly be advantageous, particularly when testing multiple SEE variants. Multi-material 3D printers can

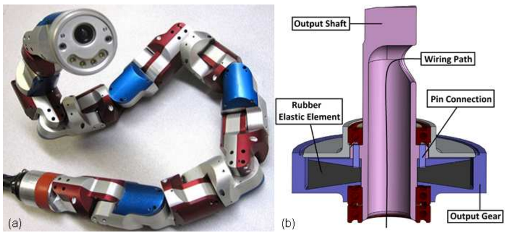

Fig. 1. (a): Unified Snake Robot [5]. (b) Cross-section of SEE [2]. Note the tapered shape of the rubber element. Bottom and top of rubber element fixed to gear output and output shaft respectively.

incorporate a range of mechanical properties (from rigid to flexible) into a single printed part [6], making it possible to print the entire SEE as an integrated unit. Of course, the viability of this approach depends on the mechanical properties of the resulting SEE. A 3D printed linear spring was successfully employed in Ref. [7] but it was not extensively characterized. Here we present the results from preliminary testing and characterization of the first 3D printed torsional SEEs.

2 Methods

2.1 Manufacture

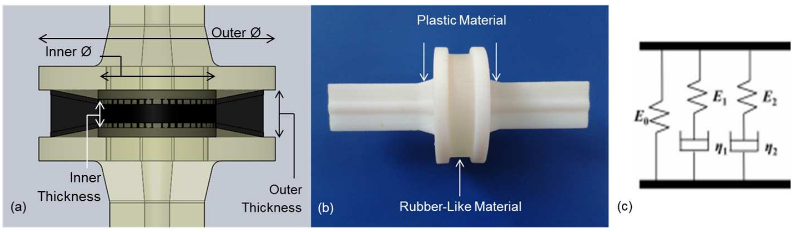

Fig. 2. Cross section of SEE CAD model. Inner Diameter=25mm (constant), Outer Diameter=45mm(constant) (b) 3D Printed SEE. (c) diagram of 5 part Weichert model [9].

We produced a total of four SEEs (two copies of two different variants) based on Rollinson's design [5]. Both variants have a similar tapered profile (see Fig. 2a) and have the same inner and outer diameter. Arms extend from both plates for attachment to the test rig. The first variant has an outer thickness of 10mm and inner thickness of 8mm, while the second has an outer thickness of 12mm and inner thickness of 10mm. The SEEs were printed using a Stratasys Objet1000 [6], using the rigid "VeroWhitePlus" material for the end plates and arms, and flexible "TangoPlus" for the spring itself (see Fig. 2a,b).

2.2 Testing

The SEEs were subjected to rotary step strain tests using an Instron E10000 [8]. One end of the SEE is fixed into the Instron's stationary base plate and the other to the rotating chuck. Each test starts from an equilibrium position (zero input angle) followed by a "step" rotation (over 100ms) to either 5° or 10° which is held for 20 seconds before returning to zero and recording data for another 20 seconds. This is repeated three times for each spring, giving six samples of step test data (three up and three down). The time, angle and torque data are logged at a frequency of 50Hz. We observed, however, that the Instron's control system produces an imperfect step in which the angle overshoots the set point as shown in Figure 3a. This is taken into account during characterization.

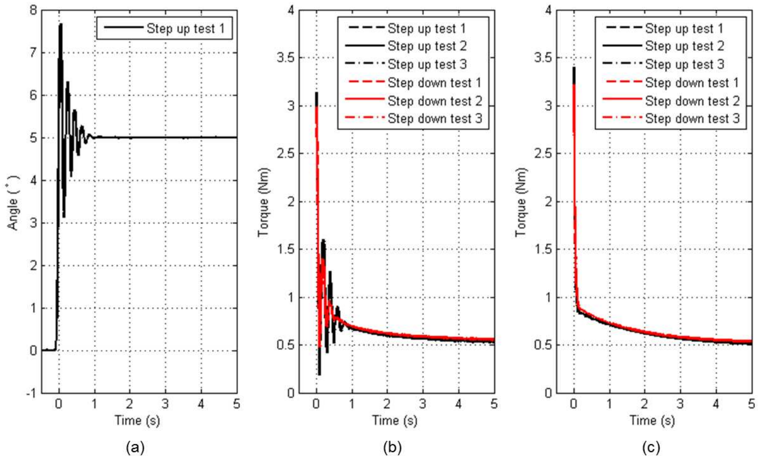

Fig. 3. (a) One sample of angle data from step test. Notice step oscillates and is therefore imperfect (b) Six samples of raw data from three iterations of 5° step test for 10mm thick SEE. (c) Line of best fit for each sample. Note the strong correlation between all six tests, whether they are step up or step down results.

2.3 Characterization

Based on an initial examination of the torque data, we concluded that our SEEs were exhibiting classic viscoelastic behavior in which an initial stress peak was followed by stress-relaxation down to a steady state value. To characterize the SEE behavior, we followed a two-step process. First, we assumed that the input angle was an ideal step and used Matlab to fit the stress-relaxation curve. We found that a double exponential produced a good fit, so we concluded that a five-element Weichert Model (Fig. 2c) was appropriate to model the viscoelastic behavior. For each spring, we performed this fitting process on each of the stress-relaxation curves (see Fig. 3), took the median across the six samples and used this to calculate the spring and damper constants for the Weichert Model. The second step in our characterization was to fine-tune the model parameters based on the real angle and torque data. We implemented a function that simulates the model's response to the actual recorded angle data for a given set of Weichert parameters before comparing this to the recorded torque data to calculate an error score. We then used Matlab's "fminsearch" function to optimize the model parameters from the first step. This step significantly improved the model fit, as shown in Figure 4. This was done independently for each of the three experiments on each SEE and the results were used to obtain the median values and standard deviations given in Table 1.

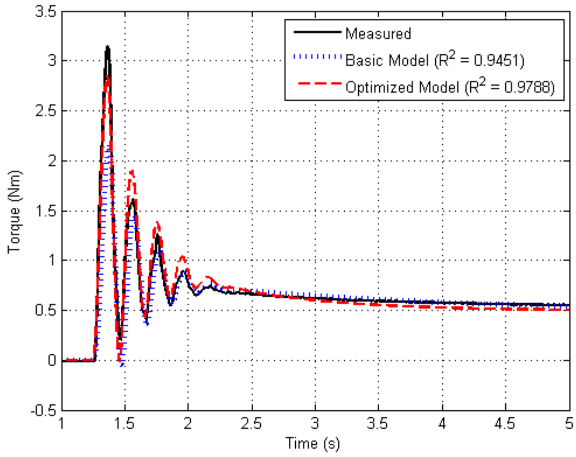

Fig. 4. 1 sample of real SEE step test data compared to basic and optimized simulation.

3 Results

As shown in Figure 3b, the step response of a single SEE is repeatable. While there is some minor difference between the up and down steps, the three repeats in each direction are virtually indistinguishable. Furthermore, as shown in Figure 4, the 5-element Weichert Model reproduces the SEE behavior well, particularly once the parameters have been fine-tuned. Table 1 summarizes our results for all four SEEs and demonstrates their repeatability. There are some anomalies relating to K_2 values, but these account for the fast adaptation which occurs in the first 100ms and are therefore of least significance. Here we will focus on the first three parameters. The first thing to note is the repeatability of behavior for a specific SEE, as indicated by the very small standard deviation values. Furthermore, the parameters obtained from 5° and 10° steps on the same SEE are virtually identical (as they should be), which confirms the validity of

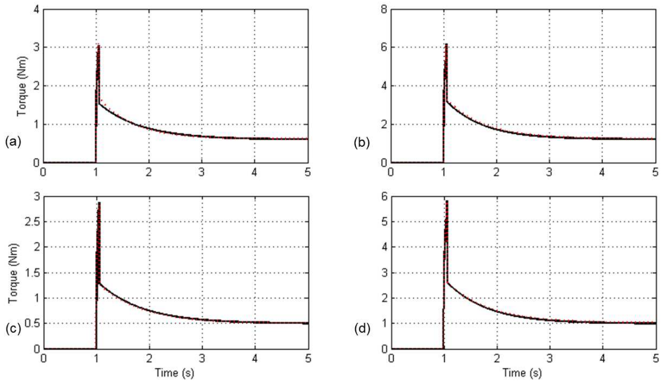

Fig. 5. Simulated results for two SEE samples in response to an idealised step input that ramps up to its final value over 50ms with no overshoot. (a,c) 5° step; (b,d) 10° step; (a,b) 10mm Outer Thickness. (c,d) 12mm Outer Thickness.

our computational characterization method. The second thing to note is the repeatability across multiple copies of the same design. Comparing the parameters for SEE1 and SEE2 of each size, we can see that both copies are very similar, despite being printed several weeks apart. This suggests that multi-material 3D printing is a relatively consistent process.

As can be seen from Table 1 and Figure 5 there is a relationship between the thickness of the SEE and its performance. In particular, the spring constants K_0 and K_1 decrease with increasing SEE thickness, consistent with the fact that the material in a thicker SEE undergoes less shear strain for a given angular deflection.

Table 1. Spring and Damping Constants across all SEEs. Values given as median ± standard deviation.

		10mm Outer Thickness				
		K_0	K_1	C_1	K_2	C_2
SEE 1	5°	6.826±0.024	11.18±0.023	8.926±0.099	417.1±71.86	0.863±0.003
	10°	6.918±0.041	11.81±0.087	8.212±0.116	1345±341.5	0.855±0.001
SEE 2	5°	7.062±0.037	12.85±0.182	8.249±0.088	2339±3031	0.810±0.001
	10°	7.080±0.040	12.32±5.835	8.628±4.068	1116±540.0	0.809±2.825
		12mm Outer Thickness				
		K_0	K_1	C_1	K_2	C_2
SEE 1	5°	5.672±0.016	9.342±0.072	7.752±0.057	8924±2413	0.907±0.001
	10°	5.670±0.033	9.646±0.054	7.354±0.074	9046±32.76	0.912±0.001
SEE 2	5°	5.703±0.042	9.045±0.399	7.264±0.105	8945±24.70	0.898±0.002
	10°	5.800±0.009	9.511±0.077	7.458±0.049	8945±50.94	0.903±0.001

4 Conclusion

It has been proved in this paper that torsional SEEs can be created using multi-material 3D printing. These also perform consistently as shown in Figure 3, as well as repeatedly over separate prints (Fig. 5). It has proved possible to accurately simulate their behavior, allowing responses of SEEs under different circumstances to be computationally investigated. Another point of note is that the Rollinson SEE's single spring constant of 5.78 Nm/rad (0.101Nm/°) [5] is lower than the similar scale 10mm printed SEE steady state spring constant (6.826-7.080 Nm/rad) but the same as the 12mm SEE (5.67-5.8Nm/rad). This shows that while the material in these 3D printed SEEs is slightly stiffer than the original molded rubber, designs can be modified and manufactured easily and quickly to achieve desired properties. It would be worth altering other dimensions within the SEE design in future work to analyze how the performance can be altered.

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