

Soft and Monolithic Variable Stiffness Clutches for Serial Elastic Actuators

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Abstract

Series Elastic Actuators (SEAs) and Variable Stiffness Actuators (VSAs) are pivotal for safe human-robot interaction and energy efficiency. However, traditional designs often suffer from high mechanical complexity and a large number of components. This work introduces a monolithic variable stiffness clutch to address this limitation. The bistable, metamaterial-based clutch utilizes a circular arrangement of double-clamped curved beams that allow the clutch to be manually reconfigured between two stable states via elastic snapping. Experimental validation using 3D-printed TPU samples demonstrates that the clutch successfully toggles between distinct torsional stiffness regimes. Results show that "normally-open" fabricated clutches achieve higher stiffness changes of 8.4 Nmm/° (0.48 Nm/rad) compared to a "normally-closed" version. This shows that the fabrication state significantly influences the performance of the metamaterial. The demonstrated variable stiffness property of the clutch offers a customizable, low-part-count solution for retrofitting or integrating tunable compliance into robotic actuators.

1 Introduction

Robots interacting with humans or their environment require safe and efficient actuation. A key property in interaction is the compliance of a body and its actuators. While higher stiffness in actuators allows for very controlled and precise movements, introducing compliance can reduce vibrations and increase the safety of interaction as well as the energy efficiency of the system. Series elastic actuators (SEAs) utilise springs and other elastic components to address these challenges physically. Changing conditions, tasks, and environments further motivated the development of methods for stiffness modulation in system [1, 2]. Variable stiffness actuators (VSAs) allow tuning the actuator's properties during use, thus leveraging the advantages of SEAs [3]. SEAs and VSAs both feature an elastic element connecting the motor to its load. This enables energy to be stored and released as required, allowing the system to react to disturbances and limit the actuator's power for inherent safety. State-of-the-art VSAs, however, are complex devices composed of a large number of components [4, 5, 6]. This work introduces an alternative approach to VSAs, leveraging the stiffness change of a monolithic, bistable metamaterial that acts as a clutch between the motor and output shaft. This clutch can be manually reconfigured by opening and closing the element. Depending on the state, the clutch shows different torsional stiffness, making it ideal as a coupling element between actuator and load. The clutch is designed to be bistable, meaning it can hold two distinct states, which are switched through elastic deformation. By design, the load axis is decoupled from the reconfiguration mechanism. Therefore, the clutch can either be added to an actuator to retrofit it or it can be directly



Figure 1 3D printed sample of the NC-clutch in closed (left) and open (right) state

integrated into the actuator. The series configuration of the motor and the variable stiffness clutch thus depicts a variable stiffness series elastic actuator. Different robotic applications require variable-stiffness actuators with different specifications. The monolithic design enables the clutch to be customised and fabricated quickly, making it easy to be replaced and exchanged in case of wear or changing applications.

2 Methods

2.1 Design and Fabrication

The design of the variable stiffness clutch is based on the concept of non-linear metamaterials [7]. In particular, we base our design on a unit cell with characteristic double-clamped, curved beams [8]. These sine-shaped beams in each unit cell lead to a non-linear response of the metamaterial under tensile load, causing the unit cell to snap into a second, metastable state. This state is maintained until a critical opposing force is applied, causing the unit cell to snap back, which again changes the state of the clutch. Recent work showed that the state change of a planar metamaterial composed of such unit cells exhibits different shear stiffness in different states [9]. We follow an approach from literature by arranging four unit cells on a circular pattern to form a cylindrical topology that suits the application of a clutch [10, 11]. We chose the following dimensions of the unit cell:

Parameter	Dimensions
Outer diameter	33 mm
Inner diameter	25 mm
Thickness of the sine-shaped beams	1 mm
Height of the vertical beams	14 mm
Width of the vertical beams	4 mm
Gap height	0.5 mm

Table 1 Dimensions of the variable stiffness clutch

The bistable clutch can be fabricated in both open and closed states, which corresponds to two different application use cases: For the first option, the clutch will primarily operate in a soft configuration and is intended to be reconfigured during use to achieve greater stiffness in the VSA. The second option requires a clutch with an initially higher stiffness that can then be reconfigured to a more compliant state. In either case, the stable state should be used for the one that is likely to be used more frequently during the application. This is recommended since the clutch will undergo significant deformation in the metastable state, which will put additional strain on the structure over time. We further refer to the fabricated and stable states as "normally-open" and "normally-closed".

The clutches are FDM-3D-printed on a Prusa XL using TPU (Ninjatech Cheetah) with a Shore hardness of 95A. We use Verbatim BVOH as a soluble support material. The samples are printed with an infill of 50%, 0.2 mm layer height, a speed of 80 mm/s, a nozzle temperature of 240°C (for TPU), and a bed temperature of 50°C. Note that the infill setting only applies to the thicker vertical beams and the support rings of the clutch. The functional sine-shaped beams are unaffected by the setting due to their small thickness. All clutches are printed with their central axis perpendicular to the print bed. **Figure 2** shows the fabricated normally closed (left) and normally open (right) samples on the print bed. **Figure 1** shows the normally closed clutch in closed and open states.

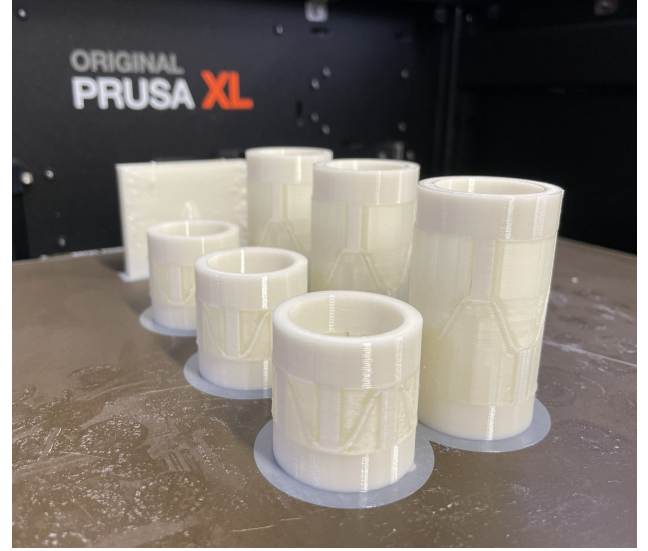


Figure 2 3D printed samples fabricated from TPU with support material (soluble BVOH) on the Prusa XL. NO-configuration (right) and NC-configuration (left).

2.2 Experimental Setup

We study the response of the clutch under load in two separate series of experiments to explore its bistability, the variable stiffness property, and the influence of the state in which it was fabricated. All experiments are carried out on a ZwickRoell zwickiLine testing machine. A first tensile test examines the bistability, and thus the state change functionality of the design. For both the NC- and NO-fabricated samples, we start the deformation of the structure from the closed state and run 10 cycles with a maximum displacement of 25 mm at a rate of 500 mm/min. Note that this means that the NO-sample is already in its metastable state at the start of the experiment.

The variable stiffness of the samples is measured with a torsional test on the same machine. **Figure 3** shows how the NO-sample is mounted in the machine: We clamp the bottom and top rings of the clutch using a rigid support part and twist the top ring by a maximum angular deflection of 5° at a rate of $\pi/40$ rad/s. Again, we run 10 cycles to prove the consistency of the structural behaviour. Both configurations of the clutch are tested in open and closed states to compare their torsional stiffness. The difference between the stiffness in the open and closed states yields the stiffness change that the clutch can achieve.

3 Results and Discussion

The results of the tensile tests are depicted in **Figure 4** and show consistency over the individual load cycles of both samples. The force-displacement curve shows that with the initial displacement, the force increases rapidly, which shows high initial resistance of the structure against load. At a displacement of ~ 3.5 mm, a maximum point is reached. Here, the maximum force of the NC sample is higher than for the NO sample, which shows the difference between a stable state (NC) and a meta-stable state

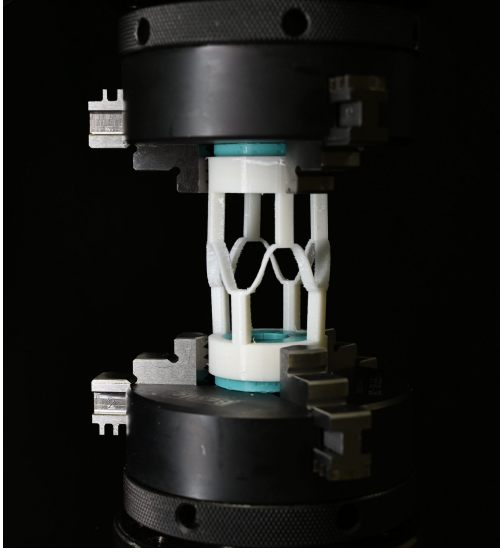


Figure 3 Testing sample (NO configuration) mounted in the ZwickRoell zwickiLine testing machine. The blue components are rigid and designed to support the clutch and allow for reliable mounting.

(NO). With further displacement, the force decreases to a point where it becomes a local minimum. Note that for the NO-sample, this minimum is at ~ -3.5 N, while the force of the NC-sample remains positive. This shows that only the NO-printed sample actively opens itself once a certain displacement is reached. From this minimum, the force continues to increase again until the maximum axial displacement of the clutch is reached at 25 mm. With unloading the clutch, the force-displacement curves of both samples cross the 0 N-level due to the hysteresis that arises from the viscoelasticity of the material. This global minimum marks the meta-stable state of the NC sample and the stable state of the NO sample. Further backward displacement deforms the clutch back into its initial, closed shape. Here, it can be observed how the force-displacement curve crossed 0 N again, implying that the structure actively pulls itself back into its initial shape. For the first stroke of each cycle, the force-displacement curves reach a higher maximum force than for all following cycles of the experiment. This is due to the viscoelasticity of the TPU material, which is also indicated by the backward motion finishing at a negative force for all testing cycles. The large hysteresis of the force-displacement curve shows the material-caused damping of the structure, with the enclosed area representing the energy dissipated. Comparing the curves of NO- and NC-configuration shows bistability for both samples (zero-crossing of the force-displacement curve). However, the results also show that the bistability is more pronounced for the NO sample.

Figure 5 and **Figure 6** show the results of the NC- and NO-configurations in the torsional test. In both cases, the slopes of the ten cycles indicate higher stiffness for the open state compared to the closed state. This matches the results for planar metamaterials with the same unit cell geometry [9]. The hysteresis of the samples again results from the damping of the TPU. However, the experiment

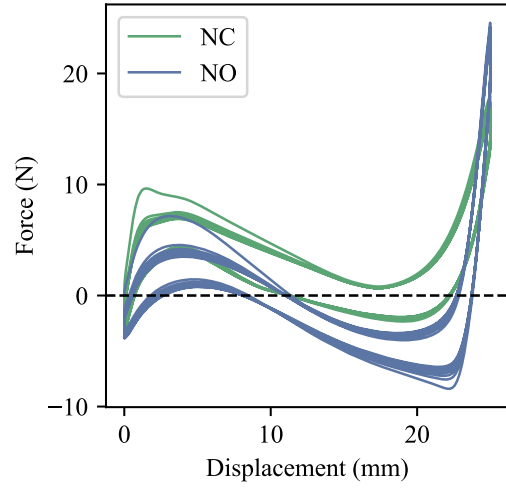


Figure 4 Results of the tensile test on the bistability of the variable stiffness clutch with 10 cycles. The Figure shows the force-displacement curves of the NC-printed sample (green) and the NO-printed sample (blue).

shows a significantly more pronounced change in stiffness for the NO-printed sample, where a maximum torque of 60 Nmm is reached at the angular displacement of 5° in the open state (23 Nmm for the NC-configuration). This leads to a stiffness 12 Nmm/ $^\circ$ for the open state of the NO-, and 4.6 Nmm/ $^\circ$ of the NC-configuration. The closed state shows very similar results for both cases, with a maximum torque of 18 Nmm in the NO-configuration and 19 Nmm in the NC-configurations, leading to a torsional stiffness of 3.6 Nmm/ $^\circ$ and 3.8 Nmm/ $^\circ$, respectively. Therefore, the achievable stiffness change with the variable stiffness clutch is 8.4 Nmm/ $^\circ$ (0.48 Nm/rad) when printed in NO-configuration and 0.8 Nmm/ $^\circ$ (0.05 Nm/rad) when printed in NC-configuration. This clearly indicates that the structure should be fabricated in the open state to generate a usable stiffness change between the two states.

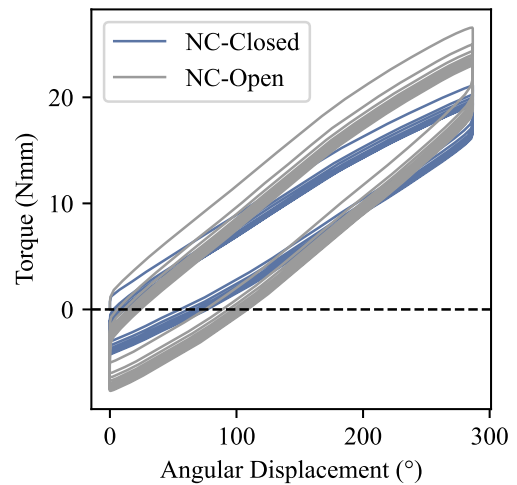


Figure 5 Results from the torsional test of the NC-printed, variable stiffness clutch in open (grey) and closed (blue) state.

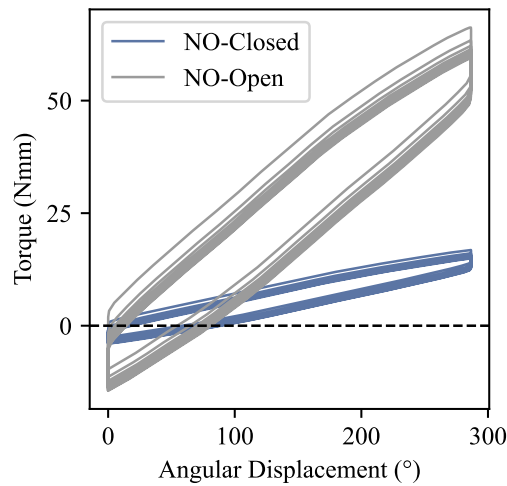


Figure 6 Results from the torsional test of the NO-printed, variable stiffness clutch in open (grey) and closed (blue) state.

4 Conclusion

The experimental results show that the design of the monolithic clutch enables switching between two characteristic torsional stiffness values by snapping it from a stable to a metastable state. The multimaterial 3D-printing allows for automated fabrication and customizability of the clutch. Regarding the stiffness of the two clutch states, it can be concluded that, regardless of the fabrication state, the open state exhibits higher stiffness than the closed state. However, the normally-open configuration leads to a substantially larger change of torsional stiffness between the open and closed state (0.48 Nm/rad). We therefore conclude that in order to obtain maximum stiffness change in the VSA, the clutch should be printed in the normally-open configuration. Bistability is given for both configurations, but is more pronounced for the NO sample. Based on this, we will aim to maximize the achievable stiffness change with the variable stiffness clutch. For this, we will systematically study the parametric geometry of the design and optimize it for both bistability and stiffness change. We will then also study different ways to trigger the state change of the clutch, following both an actuated and a passive strategy. This way, we will explore applications for the variable stiffness clutch and leverage the advantages it promises.

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