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A Variable Stiffness Joint With Electrospun P(VDF-TrFE-CTFE) Variable Stiffness Springs

Raffaella Carloni^{ID}, Valerie I. Lapp, Andrea Cremonese^{ID}, Juri Belcari, and Andrea Zucchelli

Abstract—This letter presents a novel rotational variable stiffness joint that relies on one motor and a set of variable stiffness springs. The variable stiffness springs are leaf springs with a layered design, i.e., an electro-active layer of electrospun aligned nanofibers of poly(vinylidene fluoride-trifluoroethylene-chlorotrifluoroethylene) [P(VDF-TrFE-CTFE)] surrounded by two electrodes of aluminum and held together by inactive material. To achieve a variable stiffness, different voltages and, therefore, different electric fields, are applied to the springs. The variable stiffness springs are electromechanically analyzed to highlight the voltage-deflection and force-deflection characteristics. Finally, the springs are used in the design of a proof-of-concept variable stiffness joint prototype. Experimental results on the variable stiffness joint confirm the viability of the proposed solution.

Index Terms—Soft material robotics, compliant joint/mechanism.

I. INTRODUCTION

VARIABLE stiffness actuators are a class of actuation systems that embeds tunable physical compliance in the mechanical structure, making them the key enabling technology for robots that physically interact with an unknown dynamic environment or humans [1]. Benefits for using mechanical stiffness over active stiffness on this type of robots are energy efficiency [2], robustness [3], [4], and safety [5].

The output stiffness of variable stiffness actuators and, thus, the stiffness of the actuated joints can be changed independently of the output position. This feature is achieved by means of a number of compliant elements, i.e., springs, and a number of motors that determine how the compliance is sensed at the actuator output. The schematics of a generic rotational variable stiffness joint (VSJ) is sketched in Fig. 1, where one main motor

Fig. 1. The schematic of a generic rotational variable stiffness joint.

Fig. 2. The schematic of the proposed rotational variable stiffness joint with a variable stiffness spring.

changes the position of the load via a spring, which allows the decoupling of the load from the motor inertia, and where another motor tunes the output stiffness.

Research effort has been put into exploring different designs of variable stiffness joints, mainly following three working principles [6]: adjusting the preload of the springs [7], adjusting the transmission ratio between the springs and the output [8], and changing the physical properties of the springs, e.g., the cross-section area [9] or the active length [10].

The design of the VSJ presented in this letter falls in the third group. More specifically, we propose to use one single motor and springs, whose stiffness can be (continuously) varied by applying different voltages, yielding to variable stiffness springs. The schematics of the proposed rotational VSJ is sketched in Fig. 2, where one motor changes the position of the load via the variable stiffness spring.

The novel springs, introduced in this letter, are made of nanofibers of poly(vinylidene fluoride-trifluoroethylene-chlorotrifluoroethylene), i.e., the P(VDF-TrFE-CTFE), which is a terpolymer of the polyvinylidene fluoride (PVDF). To date, the P(VDF-TrFE-CTFE) has been used as electroactive polymer actuator or as dielectric for electric energy storage [11], but it does not show any variable stiffness property [12].

In this work, we propose to fabricate nanofibers of P(VDF-TrFE-CTFE) by classical electrospinning techniques and we show their interesting variable stiffness properties when subjected to different voltages, making them ideal for the realization

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Fig. 3. Unimorph formed by an electroactive layer of a mat of P(VDF-TrFE-CTFE) nanofibers and an inactive layer of Nylon. When a voltage is applied, the active layer contracts and the unimorph bends.

of variable stiffness leaf springs. This work is the first evidence in the literature in which nanofibers of P(VDF-TrFE-CTFE) are fabricated and used for the design of a VSJ.

The remainder of the paper is organized as follows. Section II presents the realization of the variable stiffness springs and Section III described their electromechanical characterization. Section IV presents the design of the VSJ with the variable stiffness springs. Experiments on the VSJ are reported in Section V. Finally, conclusions are drawn in Section VI.

II. THE ELECTROSPUN P(VDF-TrFE-CTFE) SPRING

In this letter, to realize variable stiffness springs, we propose to fabricate a mat of aligned nanofibers of P(VDF-TrFE-CTFE) through electrospinning technique, and to assemble it in an unimorph. More specifically, the electroactive layer of nanofibers of P(VDF-TrFE-CTFE) is deposited on an inactive layer of Nylon, as shown in Fig. 3. When a voltage is applied across the active layer, strains develop longitudinally that causes the active layer to contract. The inactive layer resists the deformation, resulting in bending [13] and in an increase of mechanical reliability [14]. Deflection and generative force of a unimorph have been shown to be mainly dependent on the dimensions, as well as the electromechanical and elastic properties of the different layers. Usually, the main design choice when optimizing the bending deformation is to adjust the thickness ratio between active and inactive layers [15].

The final design of the P(VDF-TrFE-CTFE) sample consists of an active layer of electrospun nanofibers of P(VDF-TrFE-CTFE), interleaved between two electrodes of aluminum, and held together by adhesive tape on one side and Kapton tape on the other side. The volume of the active material used per sample is given by 40.8 mm^3 , which corresponds to 54 mg of P(VDF-TrFE-CTFE). Fig. 4 shows the sample with the dimensions of the different parts. The design of the sample has been chosen by following our preliminary studies [16], [17], in which the influence of the stacking sequence of passive and active layers have been analyzed to maximize the flexural response of the samples.

III. ELECTROMECHANICAL CHARACTERIZATION OF THE ELECTROSPUN P(VDF-TrFE-CTFE) SPRING

This section focuses on the electromechanical characterization of the electrospun P(VDF-TrFE-CTFE) spring, hereafter called PVDF-based springs. More specifically, by means of the characterization, the variable stiffness properties of the

Fig. 4. The electrospun P(VDF-TrFE-CTFE) sample in front (top) and section views (bottom), and relative dimensions.

spring are highlighted. The characterization consists of two experiments:

- Voltage-deflection characterization, where different voltage signals are applied to the PVDF-based spring sample and the resulting deflection is measured. This is done to find the relationship between the applied electric field and the developed strain and, thus, to model the sample's dynamic behavior.
- Force-deflection characterization, where different displacements are imposed on the PVDF-based spring sample and the resulting force is measured at different voltages. This is done to find the force-deflection curves at different voltages, showing different stiffness characteristics and, therefore, variation of the stiffness.

For the electromechanical characterization, the PVDF-based spring sample is mounted in a sample-holder by means of which the voltage can be applied to the sample. The sample is clamped in the sample-holder and its free span is of 52 mm.

A. Voltage-Deflection Characterization

For the voltage-deflection characterization, the sample-holder is put in a box that provides safety and prevents air flows from influencing the deflection of the samples. When different voltages are applied, the deflection of the samples is measured via a microscope, on the top of which a camera is mounted and records the image of the microscope. The resulting video is fed to a computer using a video grabber that converts it to a digital format. The deflection recorded in the video is analyzed in Matlab (Mathworks, USA) using a point tracker script. The deflection of the sample is the vertical displacement Δy , i.e., the deflection of the tip, as shown in Fig. 3, while the horizontal displacement Δx is disregarded.

To apply different voltages to the sample, a conditioning circuit is interfacing the high voltage (HV) generator with a Windows PC running the modeling and simulation software 20-sim and the 20-sim 4C for the automatic C-code generation (Controllab Products B.V., The Netherlands). Different signals can be applied to the sample, such as step or ramp inputs.

Fig. 5 shows the measurement set-up for the voltage-deflection characterization. More specifically, the left figure shows the sample bended under the microscope and the camera, while the right figure shows the signal conditioning scheme between the PC and the sample.

Fig. 6 shows the behavior of one sample when different voltages are applied to it. More specifically, Fig. 6(a) shows the behavior when a step input of 500 V is applied, Fig. 6(b) when a

Fig. 5. Measurement set-up for the voltage-deflection characterization. (a) The sample is under the microscope and the camera. (b) Signal conditioning for applying different voltages to the sample and for recording the images while it bends.

Fig. 6. Voltage-deflection characterization for one electrospun PVDF-based spring sample. (a) Step input of 500 V. (b) Step input with steps of 100 V. (c) Ramp input with instantaneous unloading. (d) Ramp input with slow unloading.

step input with steps of 100 V is applied, Fig. 6(c) when a ramp input with instantaneous unloading is applied, and Fig. 6(d) when a ramp input with slow unloading is applied. Every test is repeated three times to show repeatability of the behavior of the sample.

From Fig. 6, it can be observed that, when constant steps of 100 V are applied, the bending response is not proportional to the voltage level but approximately proportional to the square of the applied electrical field. This quadratic relationship between electric field and strain suggests that the active material can be considered as electrostrictive.

The samples exhibit creep behavior, which means that the material continues to bend after the voltage has reached a steady level. Correspondingly, the samples do not immediately return to their initial strain level after the voltage input returns to 0 V. The rate of creep decreases logarithmically with time. Moreover, the samples show hysteresis in the loading/unloading phases. The loading phase has a lower time constant than the unloading phase, which means that it takes longer for the sample to settle back to its original position than it took to move to its maximum

Fig. 7. Hammerstein model of the PVDF-based spring sample.

Fig. 8. Hammerstein model of the PVDF-based spring sample of Fig. 6.

deflection position. Overall, the time dependency is due to the design of the samples, i.e., the chosen passive materials (Kapton, aluminum foil, and adhesive) and the stacking sequence of the different layers.

B. Dynamic Model

By using the experimental data described in the previous section, the dynamic behavior of the sample is modeled.

From Fig. 6(b), it can be noted that the sample exhibits a nonlinear viscoelastic behavior and, more specifically, that the deflection response consists of a nonlinear instantaneous elastic response and a slower viscous response. Therefore, the sample can be described by a Hammerstein model [18], as sketched in Fig. 7. The nonlinear block $f(V)$ describes the instantaneous elastic response and is chosen as a polynomial function acting on the input voltage V with unitary gain. The linear block $G(s)$ describes the slow viscous response and it is chosen as a transfer function with two poles and two zeros. The Hammerstein model of the sample characterized in Fig. 6 is given by

$$f(V) = -4.455 \cdot 10^{-10} V^3 + 5.172 \cdot 10^{-7} V^2 + \\ -2.251 \cdot 10^{-6} V - 9.978 \cdot 10^{-4} \\ G(s) = \frac{-0.385s^2 - 14.02s + 1433}{s^2 + 69.26s + 49.39}$$

These expressions lead to a 94.55% correspondence between the model and the experimental data, as shown in Fig. 8.

C. Force-Deflection Characterization

In the force-displacement experiment, different displacements are imposed on the sample while its tip pushes on an analytical balance and the resulting force is measured. This is done while 0 V, 400 V, and 700 V are applied to the sample. The sample is mounted on the sample holder which is placed

Fig. 9. Measurement set-up for the force-deflection characterization.

Fig. 10. Force-deflection characterization for the electrospun PVDF-based spring sample - By applying different voltages the samples show a stiffness variation. (a) Force-deflection linear interpolations for different voltages. (b) Standard deviations.

horizontally so that the tip of the sample vertically presses against the scale plate. The scale plate is covered with plastic to prevent electrostatic effects between the charged electrodes of the sample and the metal measuring pan of the balance. The analytical balance is covered with a plastic box to prevent air flows disturbing the signal. The entire set-up is placed on an optical table to prevent vibrations from influencing the measurement process. This scenario is shown in Fig. 9.

The experiments were started after a waiting time of approximately one hour during which gravity bent the sample. Only after this initial waiting time, data would be collected. A vertical displacement is imposed on the sample, from 0 to 5 mm with variations of 0.5 mm. After a waiting time of 10 minutes, the value of the balance was read and the next displacement was applied. A total of 10 measurements have been recorded. Matlab was used to find a linear function of the form that corresponds to the acquired force.

Fig. 10 shows the force-deflection interpolating lines for different voltages and the relative standard deviations. From the figures, it can be observed that the higher the applied voltage is, the higher the generative forces are for a certain imposed deflection. This means that the samples get stiffer as the electric field increases. The stiffness can be determined by finding the slope of the acquired linear interpolating curves, i.e., 225 mN/m at 0 V, 393 mN/m at 400 V, and 417 mN/m at 700 V. The average standard deviations are 36.09 μN at 0 V, 58.14 μN at 400 V, and 28.09 μN at 700 V.

Fig. 11. The variable stiffness joint (front and back views).

IV. THE VARIABLE STIFFNESS JOINT

In this section, we propose the design of a novel rotational VSJ that makes use of the electrospun PVDF-based variable stiffness springs. Since the stiffness value of the samples is very low, the goal is to design a VSJ that is as light as possible and such that the friction between the different components is as low as possible. The final design of the VSJ prototype is shown in Fig. 11.

The basic idea is to use the samples as connection element between an input and an output. Input and output are in relative motion between them, thus, when the input spins thanks to the motor, the output spins with a motion law that depends on the properties of the connection element between them, i.e., the sample. As the samples are very thin beam able to get lightly shorter and bend, the idea is to fix one end of the beam to the input and fix the other end of the beam to the output. This way the sample is able to get shorter and bend, and to move the output once the input starts rotating. Based on the stiffness value of the samples, it is chosen to design a VSJ, in which ten samples are placed equidistantly in a radial pattern configuration. The sample mounting is the component that acts as input and as housing for the sample holders.

To move the sample mounting, a gearbox is introduced. The driving gear becomes the new input, while the sample holder, thanks to the gear fixed on it, becomes the driven gear of the gearbox. The driven gear is a spur gear with 120 teeth, while the driving gears is a spur gear with 40 teeth, therefore the transmission ratio is given by $\tau = N_A/N_B = 1/3$, where $N_A = 40$ is the number of teeth on the input gear, and $N_B = 120$ the number of teeth on the output gear.

Fig. 12 shows the sample mounting component, with the ten equidistant housings of rectangular section, one sample holder that can be slid in the mounting so that they can rotate rigidly with it, and the gearbox.

To apply an electric field through the samples, a voltage connection between the samples and the conditioning circuit is realized. The idea is to create two parallel aluminum raceways on the surface of the sample mounting such that, one raceway is connected to the negative pole of the HV generator and the other to the positive pole by means of two cables. The two raceways are composed by pieces of aluminum tape stuck on the cylindrical surface of the sample mounting.

For this application, given the low stiffnesses and low exerted forces, a motor that spins very slowly (< 5 rpm) is needed in

Fig. 12. Samples mounting, the sample holder, and the gearbox. (a) Samples mounting. (b) Sample holder. (c) Gearbox.

Fig. 13. The VSJ and the description of the experimental set-up. (a) The VSJ with the PVDF-based variable stiffness springs. (b) Block diagram describing the experimental set-up.

order to avoid high oscillations of the samples during start and stop phases and other inertial effects that would compromise the correct operation of the VSJ. Moreover we need to know the exact position of the motor at any instant. A servomotor SM-S2309S was chosen because it is possible to control its position with high accuracy without the need of an extra close loop control. To control the angular position of the output, an encoder AS5047D is used.

The VSJ has been manufactured by means of laser cutting and 3D printing machines. The components realized in laser cutting are in Delryn material, while the components in 3D printing are in ABS plus material.

V. EXPERIMENTS

This section focuses on the characterization of the VSJ. More specifically, the characterization consists of a deflection-torque experiment, where different angular displacements (from 0° and up to 13.3°) are imposed on the samples of the VSJ and the resulting torque is measured using a load cell. Repeating this for different voltages gives the stiffness of the VSJ for different voltages. Direct measurement was chosen as the method to investigate the characteristics of the VSJ. A known input (in this case an angular displacement) is applied to the input ring of the VSJ, and the corresponding output (in this case the torque of the output ring) is measured. The relationship between input and output ring depends on the stiffness of the samples as they are the connecting element between both rings.

Fig. 13(a) shows the VSJ and the load cell for the force measurement. More specifically, a lever arm is attached to the output ring so that it is always perpendicular to the load cell. The measured force is, afterwards, converted to torque. Fig. 13(b)

Fig. 14. Arduino, load cell, and signal conditioner. (a) Arduino, load cell and signal conditioner. (b) Contact point between the load cell and the lever arm.

shows the block diagram of the signal acquisition during of the VSJ characterization. Fig. 14 shows details and different views of the measurement set-up, with the Arduino board, the load cell, and the signal conditioner.

During the deflection-torque experiment, different angular displacements are imposed on the input ring by its motor while the lever arm fixed to its output ring pushes on the load cell that measures the resulting torque. This is done while 0 V, 400 V, and 700 V are applied to the samples. This gives information about the stiffness of the joint for different voltage levels. The entire set-up is covered with a plastic box to prevent air flows from disturbing the signal. As the motor turns, the motion of the input ring is transferred through the samples to the output ring that presses on the load cell through the lever arm. The load cell measures the force and sends its recorded value through the signal conditioner back to an Arduino board. The Arduino runs to obtain angles from 0° to 13.3° of the input ring and reads the analog voltage output of the signal conditioner.

Fig. 15 shows the torque-deflection curve of the VSJ prototype when no voltage is applied to the samples. While keeping no activation on the sample, this curve highlights the behavior of the samples themselves, which is perfectly in-line with the results reported in Fig. 6. It is possible to note that the samples show a bending behavior up to 4° of deflection and, afterwards, the samples show a membrane behavior.

Fig. 16 shows the torque-deflection curve of the VSJ prototype when different voltages are applied to the samples and when the deflections are limited between 0° and $4^\circ \approx 0.07$ rad. Note that while Fig. 10(a) shows the stiffness change of one single sample, Fig. 16 shows the global behavior of the ten samples. Finally, when analyzing the behavior of the VSJ, it can be observed that thanks to the variable stiffness springs, the VSJ has increasing output stiffnesses when higher voltages are

Fig. 15. Torque response of the VSJ prototype at 0 V for deflections between 0° and 13.3°.

Fig. 16. Torque response of the VSJ prototype for different voltages for deflections between 0° and 4° ≈ 0.07 rad.

applied. The output stiffness of the VSJ can be determined by finding the slope of the acquired linear interpolating curves, i.e., 7.43 mN·m at 0 V, 16.38 mN·m at 400 V, and 25.98 mN·m at 700 V. These values bring to the linear relation between the output stiffness of the VSJ and the voltage, i.e., $K(V) = mV + K_0$, with $m = 0.026$, $K_0 = 6.968$.

VI. CONCLUSION

In this work, we propose to use variable stiffness springs for the design of a VSJ. This way the VSJ makes use of one single motor, while being able of achieving a tunable stiffness at the output joint. The stiffness variation in the springs is achieved thanks to their innovative fabrication.

The springs are realized by nanofibers of P(VDF-TrFE-CTFE) and, more specifically, they are realized as an unimorph, whose layered design is made of nanofibers of P(VDF-TrFE-CTFE) as the active material and Kapton as the elastic inactive material. The spring stiffness can be changed by applying different voltages, i.e., different electric fields. This letter is the first evidence in the literature in which the P(VDF-TrFE-CTFE) is electrospun and, therefore, its nanofibers realized, showing a very interesting variable stiffness property.

Experimental results shows that the proposed VSJ is energy efficient because, even though the required voltages are rather high, the involved currents are of the order of μA .

Future work will focus on different design of the variable stiffness spring samples to investigate how the dimensions and quantity of electroactive material enhance the performances of the VSJ, e.g., exerted output torques and dynamic behavior.

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