Toward a Novel Thermal-Based Variable Impedance Module Through Adjusting Viscoelastic Properties of a Thermoresponsive Polymer

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***Abstract*—In this article, we propose a one-of-a-kind thermal-based variable impedance module to be used towards developing a variable impedance actuator. Unlike other variable impedance actuators, where the impedance adjustment modules employ a mechanism to regulate their impedance, this novel module does it through controlling temperature of a thermoplastic polymer *Polycaprolactone*. The viscoelastic properties of *polycaprolactone* are temperature-dependent, increasing the rigidity when it is cooling down and softening when it is heating up. To change the temperature, thermo-electric Peltiers are embedded into the design. Preliminary experiments have shown that this module is able to adjust its impedance through changing the temperature. The simplicity and lightness of the proposed off-line impedance adjustment approach make it a suitable choice when the actuator's size, weight, and compactness are the main concerns. This is because the proposed design is highly scalable, and by scaling down the size of the module, its performance regarding the speed of impedance adjustment would increase.**

***Index Terms*—Variable stiffness actuators, thermoactive polymers, impedance.**

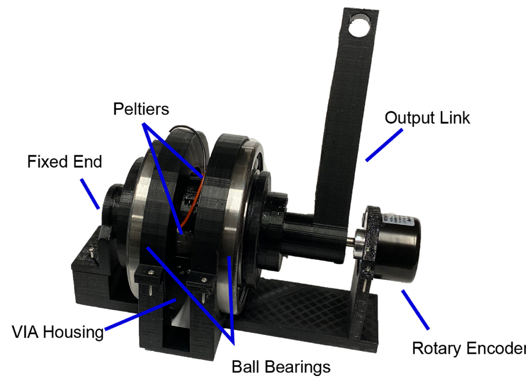

Fig. 1. Thermo-active VIM prototype constructed with 3D-printed PETG components with integrated Peltiers.

I. Introduction

Impedance is defined as resistance to motion, which has three components: stiffness, damping and inertia [1]. In *physical* Human-Robot Interaction (*p*HRI) applications, and when physically dealing with unknown environments, robotic platforms should be able to tune their level of impedance [2]. Variable Impedance Actuators (VIAs) [3] are a new drive train generation for robotic platforms that are designed to physically interact with humans. These types of actuators have the capability of adjusting their impedance (i.e., through changing stiffness [4], damping ratio [5], or sometimes even the inertia [6]), while in contact with unknown environments. This is to guarantee the safety of the humans with whom the robot is physically interacting with as well as enhancing their performance criteria [7].

Changing the parameters of the impedance is typically done by a dedicated mechanism embedded inside the actuator [8]. However, adding these mechanisms into the actuators' designs makes them bulky, heavy, and large compared to traditional rigid or Series Elastic Actuators (SEA) [9]. In this work, we present a novel idea of a thermal-based variable impedance module (VIM), Fig. 1.

The impedance of the proposed module is tuned by controlling temperature of a thermoplastic polymer *Polycaprolactone* (PCL) [10], rather than a mechanical mechanism, that is composed of springs or dampers and additional DC motor. PCL belongs to a class of polymers known as thermoplastics, which change their viscoelasticity as they move from cold (rigid) to hot (soft) [11]. In order to adjust the temperature, thermo-electric Peltiers are embedded into our design. Since a simple mechanism is required to change the impedance, this design would allow for compact and lightweight variable impedance actuation technology. This work's sole focus is on the design and implementation of the VIM for the changing of impedance, as no motor is attached for the initial study.

The organization of the paper is as follows: in Section II, design components of our proposed thermal-based VIM will be introduced. The viscoelastic properties of the proposed actuator will be modeled in Section III. Section IV presents some preliminary experimental results on our proposed VIM and finally discussion and conclusion are presented in Section V.

II. Mechanical Design and Components of the Proposed Polycaprolactone-Based VIM

A. Mechanical Design

Our VIM module, as shown in Figure 2, contains three consecutive parts: a middle part responsible for changing the viscoelastic properties of thermo-responsive material through adjusting the temperature, and one series elastic part at each side. Each series elastic part is responsible for realizing a fixed level of rotary compliance through a set of six linear compression springs that are placed the housing and the inner wheel. As for the thermo-responsive material, we use three polycaprolactone-based sponge between the inner wheel and the housing.

The thermo-active module in our proposed design has three radially-mounted thermo-electric Peltiers. The thermo-electric Peltiers are located in slots that have access to the outside environment. The reason for this mounting is so that when the inner sides of the Peltiers get cold (to reduce the temperature of PCL inside the outer ring), their outer sides get hot, and vice versa. This generated heat needs to be taken out of the system, otherwise it dramatically affects the performance of the thermo-electric Peltiers and would

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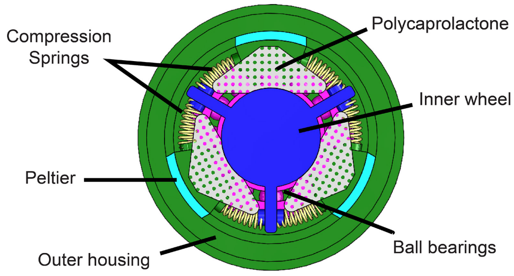
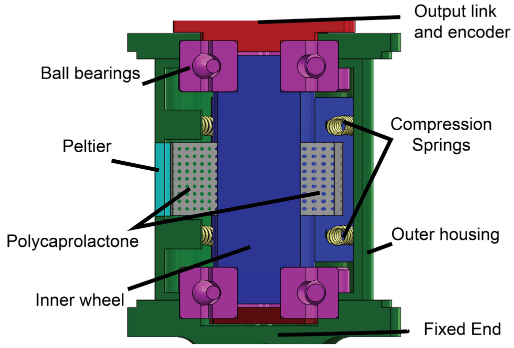


(a) Top view of VIA body



(b) Side view of VIA body

Fig. 2. CAD design of thermo-active VIA.

lead to their failure. A prototype of the proposed VIA is shown in Figure 1.

A spiked wheel is placed inside the outer ring and attached to the output link while the spikes are in contact with the PCL sponge inside the outer housing. Once the output link moves, the spiked wheel rotates inside the outer ring and presses the PCL through its spikes. Each spike is also connected to the outer ring via compression springs. Once the wheel rotates inside the outer ring due to the motion of the output link, the compression springs become deformed and thus the output link behaves compliant. Therefore, having the springs between the output link and the fixed end makes the design act like a SEA. However, the overall impedance changes from adjusting the temperature inside the outer ring and utilizes the viscoelastic properties of PCL.

Next, the two essential components of our physical prototype, the Peltier and Polycaprolactone, will be discussed in detail.

B. Components of the VIA Prototype

1) Thermo-Electric Peltiers: When an electrical current I is applied, it induces a heat flow at the cold Q_c and hot Q_h junction temperatures, and thus one side becomes hot and the other side cold, as shown in Fig. 3. The heat flow determines the temperature at each side of the Peltier based on the Seebeck effect coefficient α, thermal conductivity k, specific electrical resistance ρ, the cross-section area A and length L of n- and p-type semiconductors.

2) Properties of Polycaprolactone: Furthermore, PCL is a plastic polymer that exhibits thermoplastic properties, meaning it can be shaped and molded when heated to a certain temperature and solidifies when cooled [12]. Unlike most thermoplastics, PCL has a lower molecular weight, which allows its polymer chains to associate with intermolecular forces that rapidly weaken with increased temperatures, creating a viscous liquid [13]. PCL's stiffness changes depending on its temperature, becoming rigid when cold and soft when hot. This unique characteristic allows PCL to be reshaped and used to produce various parts through different polymer processing

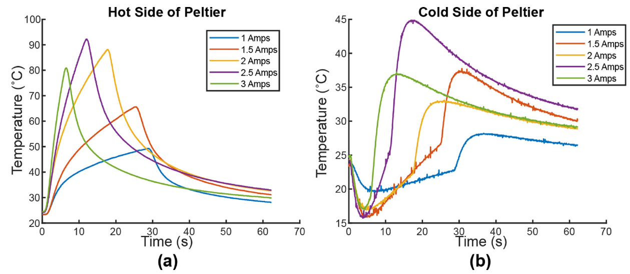


Fig. 3. (a) Heating and (b) Cooling of the Peltier at each surface.

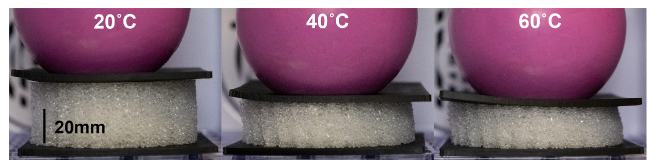


Fig. 4. Compression of polycaprolactone sponge with 4.5 kg of added weight at (L to R) 20°C (37.7mm), 40°C (25.57mm), and 60°C (23.4mm).

techniques. In order to determine the impedance variation of polycaprolactone as a function of temperature, some static tests have been done (i.e., evaluating stiffness component of the impedance) on a sponge made of polycaprolactone. In these experiments (shown in Figure 4), a known weight (4.5 Kg) was placed on the sponge while the temperature changed from 10 °C to 60 °C. The vertical deflection of the sponge was then measured and then normalized with its original thickness to determine the strain. Similarly, the weight was divided by the area of the sponge to calculate the stress.

III. Modeling the Viscoelasticity of the Proposed VIA

In order to better understand the impedance properties of our design, the viscosity and the elasticity of polycaprolactone, i.e., its storage E_1, G_1 and loss E_2, G_2 moduli (tensile and shear), as functions of temperature T have to be taken into account, through Dynamic Mechanical Analysis (DMA) [10]. DMA applied a sinusoidal strain to the PCL sample, at different frequencies. The resulting force or stress applied to the sample was measured. Then the results have been transferred to the frequency domain through Fourier transformation. In the frequency domain, the complex modulus was calculated as the ratio of the Fourier transformed stress or force to the Fourier transformed strain or displacement. The complex modulus combines both the storage and loss components. As shown in Figure 5, both tensile moduli have a sudden drop when the temperature exceeds 30°C. Below this threshold temperature, $E_2 \leq E_1$ and $G_2 \leq G_1$ imply that the elastic behaviour of the material is more dominant that its viscous property. When the temperature is higher than 45°C, polycaprolactone becomes very soft and will be a more viscous material rather than an elastic one as $G_2 \leq G_1$.

In our proposed design, compression springs around a wheel can be modeled as springs in parallel to polycaprolactone which can be modeled as a combination of a spring and a dashpot. The schematic of the VIA model is presented in Figure 6. The output link is attached to the variable impedance unit which is fixed to the base of the prototype. The variable impedance unit is composed of a damper to represent viscosity of polycaprolactone b_{PCL}, a spring to represent elasticity of polycaprolactone k_{PCL}, and a spring for the compression springs with constant stiffness K_s. The output link's position is shown by θ_L, while the position of the fixed end is zero. Similarly the torque

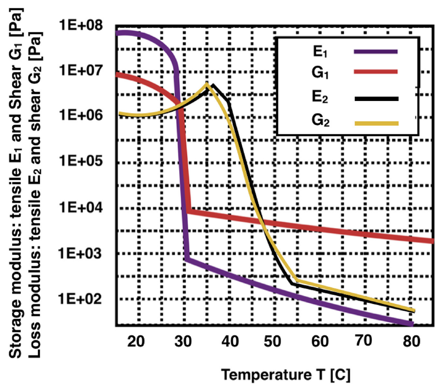


Fig. 5. Storage and Loss (tensile and shear) Moduli of polycaprolactone at different temperatures.

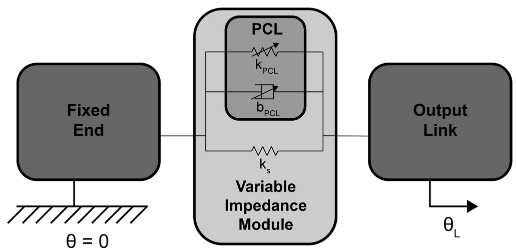


Fig. 6. Schematic model of the proposed variable impedance module.

TABLE I
SYSTEM PARAMETERS

Parameter	Value
Individual spring stiffness k_s	266.88 N/m
Total spring stiffness K_s	1.6343 Nm/rad
Distance of springs from center axis	22.57mm
Length of output link L_l	140mm
Moment of inertia of output link I_l	$2.999 \cdot 10^{-5} kg \cdot m^2$
Weight	0.58kg
Maximum angular deflection	1.0472 rad
Amount of Polycaprolactone in each cavity	1.05g
Volume of Polycaprolactone in each cavity	$11200mm^2$

of the fixed end is assumed to be zero and T_L is the output torque available at the output link of the actuator.

The equation of motion for the output link as a result of the output torque is as follows:

$$(k_{PCL} + k_s)\theta_l = I_l\ddot{\theta}_l + b_{PCL}\dot{\theta}_l + T_l \quad (1)$$

where I_L is the link's inertia.

The stiffness and damping in Equation (1) are functions of storage and loss moduli, temperature level as well as the geometric parameters of the PCL material that is enclosed in our design.

IV. EXPERIMENTAL RESULTS

A. Perturbation Test

The output link was displaced by 60° and released to return to the equilibrium position. The output link was attached to a rotary encoder, E40S6-100-3-T-24 from Atomics, with 100 pulses per revolution (PPR). The initial resting equilibrium position was calibrated to an encoder count of zero before perturbation. The deflection of the output link was captured with no PCL and PCL with varying temperatures from room temperature (22°C) to 60°C to cover the full range of viscoelasticity. A lookup table was created for the

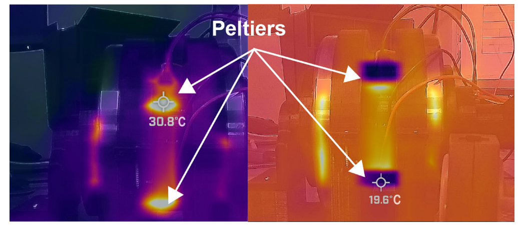


Fig. 7. Localized heating (left) and cooling (right) of the VIA from the Peltiers.

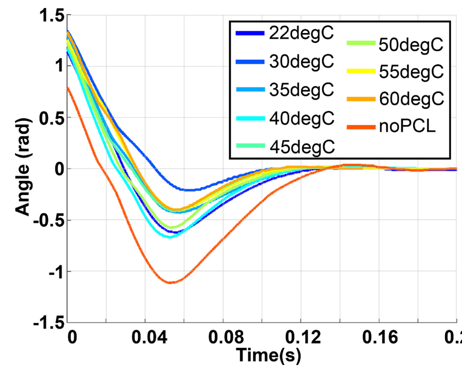


Fig. 8. Perturbation test of the VIA output link, showing deflection with no PCL, and PCL incorporated at varying temperatures.

control of the PCL temperature from the Peltier heating at varying currents, so that the Peltier would turn on, time would pass, and then the perturbation data would be collected for a desired temperature.

As the temperature increases, the settling time of the output link decreases, and the % overshoot decreases. Fig. 8 shows the output link trajectory response to the perturbations. During these perturbation tests, the output link had ~10° degrees before the PCL came into contact with the wheels and the different trials would sometimes bounce away from the equilibrium point (0 degrees). Therefore, the trailing values of these tests were used to normalize the curves so that they could be overlaid, resulting in starting values indicating 0.8-1.35 rad.

B. System Identification

Equation (1) requires knowledge of b_{PCL} and k_{PCL}, the damping and stiffness coefficients of PCL to fully describe the system. The collected data from the perturbation testing was used for comparison and validation of the model. The output link was adjusted so that the equilibrium point is horizontal, and a known weight was placed on the end to produce a known torque. Using this information, Eq. (2) could give approximate k_{PCL} values for corresponding temperatures.

$$(k_s + k_{PCL}) \cdot \theta = T_l = F \cdot L_l \quad (2)$$

where L_l is the length of the output link. Further, Eq. (1) was used to solve for the last unknown b_{PCL}.

Once the approximate k_{PCL} values were obtained, the only unknown in Eq. (1) is b_{PCL}, then $\dot{\theta}$ and $\ddot{\theta}$ can be calculated from the perturbation data in Fig. 8 to obtain the values of b_{PCL} at the varying temperatures (Table II).

The design of the VIA has the equilibrium position of the compression springs curved around the central axis (radius = 22.57mm), which caused springs to buckle and act non-linearly as increased forces were applied. Due to this, the k_s values used to calculate k_{PCL}

TABLE II
VISCOELASTIC PROPERTIES OF POLYCAPROLACTONE

Temperature (°C)	k_{PCL} (Nmm/rad)	b_{PCL} $(Nmms/rad)$
30	332.95	48.341
35	201.87	38.572
40	87.369	35.251
45	201.87	36.684
50	87.369	49.950
55	34.882	12.796
60	almost zero	22.248

(and b_{PCL}) could be inaccurate from those provided by the manufacturer. Furthermore, the geometry of the PCL fit into each cavity surrounding the central wheel showed a non-linear effect for both the k_{PCL} and b_{PCL} based on the curves obtained during system identification. The k_{PCL} followed a clear trend decreasing in magnitude as the temperature increased, and the b_{PCL} increased as the temperature increases. However, the b_{PCL} values decreased drastically at $55°C$. This sudden drop could be due to the non-linear effects observed above.

V. DISCUSSION AND CONCLUSION

This paper presents a novel idea of regulating the temperature of a viscoelastic polymer, polycaprolactone, as a way to adjust the impedance of an actuator. Controlling the temperature of polycaprolactone is done using Peltiers, and a simple design is introduced to realize the variable impedance behaviour. The simplicity and lightness of the design can open up new possibilities for developing the next generation of thermo-active variable impedance actuators for physical Human-Robot Interaction applications. The proposed actuator prototype showed capabilities of regulating both elasticity and viscosity in an off-line fashion. However, the impedance adjustment rate is still not suitable for on-line impedance adjustment. In future experiments, the step signal and sinusoidal response of the VIA must be evaluated with a motor and gearbox driving the rotation. Additionally, we will analyze the effects of scaling down the size of the actuator on the rate of impedance adjustment.

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