VARIABLE COMPLIANCE ROBOTIC JOINT

[1]Mojtaba Azadi, [2] Sangbae Kim
Mechanical Engineering Department
Azadi@mit.edu, Sangbae@mit.edu

1 Motivation

Unconsciously, animals and humans can establish their joint compliance and power output for a variety of reasons. For example, animals adjust their legs' compliance while walking, hopping and running to achieve a desired and energy-efficient gait. Understanding the principles behind compliance and power adjustment, and the possible correlation between compliance change and walking energy efficiency are essential for efficient walking gait and running gait designs as well as prosthetic and orthotic designs. We are interested in developing bio-joints that can mimic their biological counterparts in producing adjustable compliance in a relatively compact way, with feasible actuation energy and schemes.

2 Introduction

Rotary Variable-Compliance Robotic Joint (RVRCJ) introduced here is a mechanical joint that similar to any mechanical joints can transfer motion and load between input and output. Kinematic pairs (e.g. hinges, spherical joints, universal joints) are classical mechanical joints that confine some of the motions[1], [2]. Theoretical kinematic pairs demonstrate zero stiffness in the working direction and infinite stiffness along the confined directions. Compliant joints or Flexure joints [3][4] eliminate the use of kinematic pairs due to their monolithic (one-piece) nature. These joints deflect under the external load to achieve a desired motion. Compliance is achieved by devising lumped compliance, distributed compliance or instantaneous motion in the mechanism. These joints demonstrate none-adjustable low stiffness in the desired working direction and present higher non-adjustable stiffness in other directions. Actuated joints (motorized joints) such as robotic joints can demonstrate variable stiffness along the allowable direction by actively controlling the actuators. These joints are called active joints. Variable stiffness joints can also be semi-active joints. There are several variable stiffness robotic joints reported in the literature [5]. Most of the developed variable compliance technologies have slow response, they are bulky and they do not have a energy efficient scheme to vary compliance.

3 Approach

The RVRCJ (Figure 1) is a variable stiffness/compliance joint based on a new idea of using prestressable pin jointed structures. RVRCJ connects input and output shafts and provides variable stiffness about the axis of the input-output shaft.

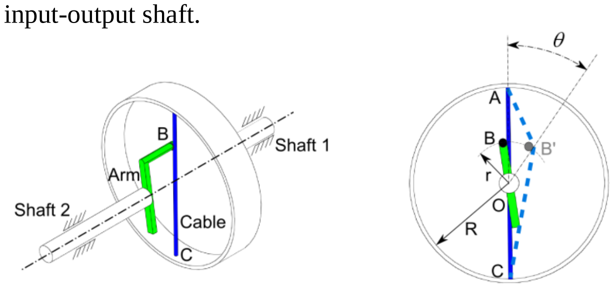

Figure 1. Schematic of the Rotary Variable-compliance robotic joint (RVRCJ)

Cable is an elastic material pulled between two points on shaft1 (points A and B on Figure 1). Cable carry tension and can be chosen from any elastic material. Arm is a rigid link located on the other shaft. It is adjustable and pushes cable at point B. Arm length is equal to r. Shafts are rigid bodies confined to have rotary motion. The arm is attached to one of the arms and cable is attached on the second shaft. Either of the shafts can work as input or output. Cable Tension (τ) is the internal force of the cable. cable tension is made by pulling the cable at one of the ends (A,C) and increase when arm push the cable at B. When arm does not touch the cable, internal force of the cable is called pretention or prestress (τ_0). When arm pushes the cable the cable force (τ)would be greater than pretention. Assume shaft 1 is fixed. Under an external CW torque M shaft2 and the arm rotate CW. The arm applies a force on the cable at point B the cable stretches and arm start rotating and reaches new equilibrium when it rotates θ degrees CW. At final configuration arm apply force on the cable at point B'. The rotation of the arm (θ) depend on three factors: 1-Elastic stiffness of the cable (e.i. size, cross section and elasticity of the cable) 2-Geometry of the joint (e.i. R,r) 3-Pretension of the cable (τ_0). The joint can rotate freely in CCW.

The rotational stiffness of a RVRCJ can be changed by two methods: 1-changing the geometry 2- changing the pre-stress of the internal mechanism that relate input and output. First method can be used to set the initial desired compliance. Second method can be used during operation for fast stiffness change. Based on the simple configuration of the RVRCJ, the resulted joint would be compact and because it is force-controlled compliance, it would be fast response.

The stiffness of the RVRCJ at the beginning ($\theta = 0$) is found from a simple formulation:

$$k_\theta|_{\theta=0} = \tau_o(\frac{1}{R+r} + \frac{1}{R-r})r^2 \qquad \textbf{Equation 1}$$

Error! Reference source not found. reveals several interesting characteristics of a RVRCJ. The initial stiffness of the joint is linearly a function of pretension (τ_o) and is not a function of elasticity of cable. The initial stiffness in CW direction can be varied from zero to infinity. When effective length of the arm is zero (arm touches middle of the cable) the stiffness is zero and the joints can rotate freely in both directions. Also when arm is at its maximum length where r=R the stiffness in CW direction is infinity. This means joint will be completely rigid in CW direction.

As soon as the arm moves the elastic stiffness starts building up gradually. The general form of the stiffness of the RVRCJ is also found. In order to improve linearity a serial spring (k_s) can be added to the joint.

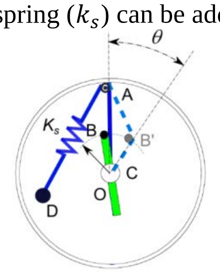

Figure 2. Another possible cable arrangement for a RVRCJ

4 Results

In order to demonstrate general characteristics of a RVRCJ a simple test setup based on the configuration show in Figure 3, was made (see Figure). A $\frac{1}{16}$ *inch* 7x19 stainless wire rope was used as the cable. The cable pretension is adjusted manually by a cable tensioner and external moment was also applied on the arm manually. The rotation (θ) and the torque applied on the arm (M) was measured by a rotary potentiometer and a 6DoF load cell, respectively.

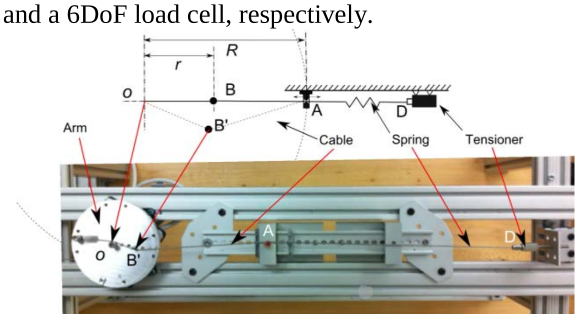

Figure 3. Test setup

Figure compares the effect of increasing pretension on the moment-angle curve of the RVRCJ. The stiffness would be the slope of this curve. Test results verified the simulation results and as it can be seen, by increasing the pretension the stiffness including the initial stiffness increases. The hysteresis seen in the experimental results originates from friction between wire rope strands, friction at pin B and mainly from fiction of the bearing of the arm. The hysteresis can be decreased by using bearings at the contact point of the pin and cable.

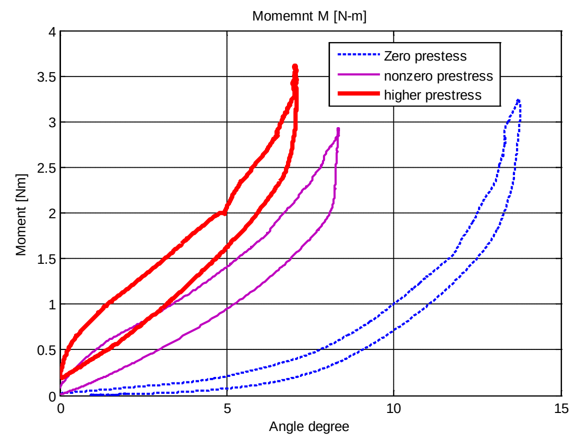

Figure 4. Experimental results for different levels of prestress

5 Best Possible Outcome

Possible applications for a RVRCJ would be in robotics and medical devices. Developing a variable stiffness series elastic actuator will be explored next. Variable stiffness joints for leg locomotion, prosthesis, orthotics can also be explored with this joint.

6 References

[1] F. Reuleaux, *The Kinematics of Machinery*. London: Macmillan and Co.

[2] J. Denavit and H. S. R., “A kinematic notation for lower-pair mechanisms based on matrices.,” *Trans. of the ASME. Journal of Applied Mechanics*, vol. 22, pp. 215-221, 1955.

[3] Larry L. Howell, *Compliant Mechanisms*. John wiley & sins, inc., 2002.

[4] S. Awtar, “Synthesis and analysis of parallel Kinematic XY flexure mechanisms,” Massachusetts Institute of Technology. Dept. of Mechanical Engineering., 2004.

[5] B. Y. R. V. A. N. Ham, T. G. Sugar, B. Vanderborght, K. W. Hollander, and D. Lefeber, “Compliant actuator designs,” *IEEE Robotics & Automation*, vol. 16, no. 2, pp. 81-94, 2009.