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A Novel Actuator with Adjustable Stiffness (AwAS)

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Abstract—**This paper describes the design and development of a new actuator with adjustable stiffness (AwAS) which can be used in robots which are necessary to work close to or physically interact with humans, e.g. humanoids and exoskeletons. The actuator presented in this work can independently control equilibrium position and stiffness by two motors. The first motor controls the equilibrium position while the second motor regulates the compliance. The novelty of the proposed design with respect to the existing systems is on the principle used to regulate the compliance. This is done not through the tuning of the pretension of the elastic element as in the majority of existing system but by controlling the fixation of the elastic elements (springs) using a linear drive. An important consequence of this approach is that the displacement needed to change the stiffness is perpendicular to the forces generated by the springs, thus this helps to minimize the energy/power required to change the stiffness. This permits the use of a small motor for the stiffness adjustment resulting in a lighter setup. Experimental results are presented to show the ability of AwAS to control position and regulate the stiffness independently.**

I. INTRODUCTION

WITH robots now poising to emerge from their industrial cages and move into close vicinity with humans, safety poses great allegations. To address these concerns, researchers try to find ways to prevent robots from harming people. Rigidity of industrial robots potentially presents mechanical menaces to humans with whom robots are supposed to co-operate. Most of the solutions proposed have a common objective which is the reduction of the impact forces during accidental collisions between the robot and its environment or humans. The series elastic actuator (SEA) [1] achieves this by introducing compliance between the actuator and the robot which decouples the large actuator inertia from the load thus reducing the apparent inertia and therefore the collision forces during the impact. In the Distributed Macro-Mini Actuation system (DM2) [2] two separately located actuators generate the torque in low and high frequency domains. The low frequency actuator which is based on the SEA concept is located at the base to reduce the reflective inertia and the high frequency actuator is a servomotor located at the joint. Elastic rotary actuator [3] is a compact rotary version of SEA which has been realized in a small scale.

In addition to the safety, in periodic like trajectories the existence of elastic elements act as storages for energy which can be fed by the kinetic energy or the gravitational potential energy of the system. This energy then can be returned back to the system within the next cycle. This can assist to reduce the energy supplied by the actuation system. For instance walking which is an essential task for humanoid robots such as bipeds and exoskeletons is a kind of periodic motion. It is obvious that for humanoids the needed level of compliance is not fixed all the time and also the walking frequency is based on the variable desired speed. To optimize the energy storage and reuse the system should have the ability to regulate its compliance. This implies the need of variable compliance actuators.

As in these types of joints two parameters, position and stiffness have to be independently controlled; two actuators per joint are needed. One approach for implementing these joint is the use of a bio-inspired antagonistic configuration of two actuators of equal size combined with elastic elements exhibiting a nonlinear force to deflection behavior. The biological inspired joint stiffness control is a rotational joint, actuated by two series elastic actuators with nonlinear springs [4]. In the electromechanical Variable Stiffness Actuator (VSA) developed by [5] a timing belt tensioned by springs actuates the link using two DC motors in an antagonistic arrangement. In VSA-II [6] a four-bar mechanism is used to get a nonlinear torque-displacement characteristic [6]. Pleated Pneumatic Artificial muscles (PPAM) [7] have been antagonistically used in biped Lucy [8] as compliant actuators. In these types of robotic joints changing the position is done by co-rotation of two actuators while tuning the stiffness is based on their relative motion, counter-rotation of two actuators in one direction makes the joint more compliant and in other direction make it stiffer. While these actuators are able promptly change the stiffness,

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the main drawback of these antagonistic setups is their energy efficiency as both actuators are directly counteracting with the elastic element's force and therefore to change the stiffness the needed energy is considerably high. This is not the case only for antagonistic setups. For instance in MACCEPA [9] and MACCEPA 2.0 [10] the motors which tune the stiffness by setting the pretention of the spring, directly counteract with the springs. In the Variable Stiffness joint (VS-joint) [11] developed by DLR two motors of different sizes change the link position and stiffness preset separately, but presetting the stiffness requires the smaller motor to compress the springs directly. Therefore even at equilibrium position changing the stiffness requires energy. Furthermore stiffness is mostly a function of angular deflection and the role of the second motor in changing the stiffness by tuning the preset is much less than that of angular deflection. Therefore at a certain angular deflection, stiffness can be changed within a small range. In the mechanism proposed by [12] the compliance can be tuned through changing the aspect ratio of a flexible beam. Even this can be done easily with low energy consumption this mechanism can regulate the stiffness to only two discrete values and not any intermediate value. The Variable Stiffness Unit (VSU) developed by [13] is composed of a motor, two rings that consist of arc-shaped magnet separated by spacers and a linear guide to change the cross-sectional area of the two rings. The stiffness of the joint is varied by changing the overlapping area of the magnets. In VSU there is no spring and the magnet force virtually replicates the spring like behavior. The energy consumption to tune the stiffness for VSU is low. The main drawback though is the small range of stiffness.

In this work we proposed a new design principle for implementing a variable stiffness actuation unit which permits the realization of a unit capable of reproducing a wide range of stiffness. A novel feature of the proposed Actuator with Adjustable Stiffness (AwAS) with respect to the existing systems is on the mechanism used to regulate the compliance. This is done not through the tuning of the pretension of the elastic element as in the majority of the existing implementations but by controlling the fixation points of the elastic elements (springs) using a linear drive which tunes the stiffness based on the variable arm concept an idea originated from the work in [3]. Based on its mechanism principle, AwAS can be considered as a *mechanically controlled stiffness actuator* according to the categorization made by [14].

II. AwAS: MECHANISM CONCEPT

A. Principle of Operation

In a traditional design of two springs placed in an antagonistic setup, stiffness is changed by controlling the pretension of the springs. Extending both springs makes the joint stiffer; relaxing both springs makes the joint more compliant. The connection mechanism, which can be a lever arm or pulley, is constant in such a design. The novelty in the AwAS design is that for tuning the stiffness the pretension of the springs is held constant, while the fixation points of the two springs with the output link are changed. As can be seen in Fig. 1 two antagonistic springs are connected on one side to the intermediate link and on the other side to the output link. The intermediate link is rigidly attached to the main joint motor (hereafter called M1). The lever arm is defined as the vertical distance between center of rotation of the link and the point at which springs are attached. A guiding mechanism driven by another motor (hereafter called M2) allows the control of the length of the arm by moving the two springs toward to (to reduce stiffness) and away from (to increase stiffness) the center of rotation.

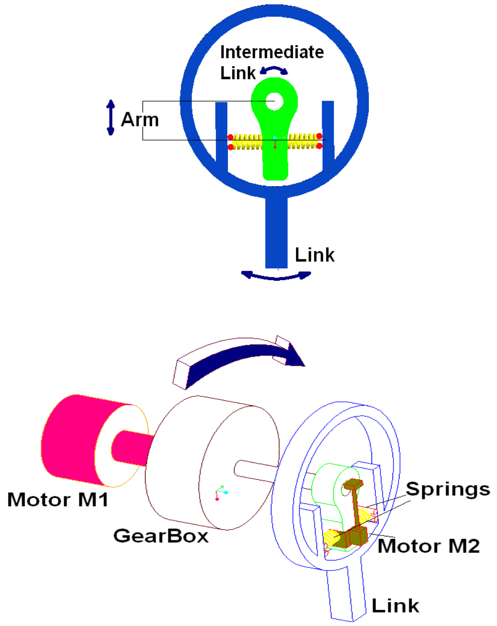

Fig. 1. AwAS-principle of operation (left), conceptual design (right)

The sum of the lengths of the two springs is always a constant, so the pretension does not change when controlling the stiffness. When the output link is in its equilibrium position (the angular position where zero torque is generated, so when the extension of both springs is equal), then the force generated by the springs is perpendicular to the displacement needed to change the stiffness. This has the important consequence that in principle no energy is needed to change the stiffness. In different designs the force is always parallel to the displacement requiring a strong motor and sufficient amount of energy to change the stiffness. In reality, the presence of friction has to be overcome. In addition if the joint is not in the equilibrium position the force generated by the spring has a small component parallel to the displacement and a small amount of energy is needed. However due to this property the motor controlling the stiffness can be significantly smaller than that in other designs of variable stiffness actuators. An additional advantage of this design is that it does not require the use of non-linear springs or mechanisms to provide the nonlinear force/displacement profile which is necessary for the stiffness regulation.

B. Stiffness Regulation

For the derivation of the mechanism stiffness as a function of the lever arm length we consider the actuator schematic representation shown in Fig. 2

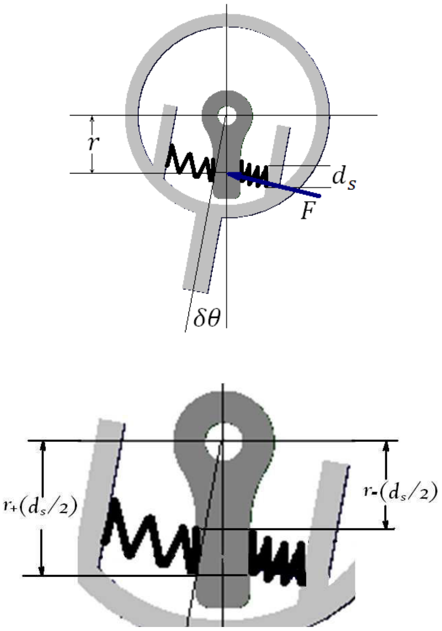

Fig. 2. AwAS at un-equilibrium position

Where the parameters introduced in Fig. 2 represent:

r = arm, d_s = spring's diameter, $\delta\theta$ = angular deflection; the angular difference between link and intermediate link, K_s = spring's rate, F = resultant force due to spring's deflection, p = spring's pretension, δX = spring's deflection, K = Stiffness

The resultant forces on the intermediate link at the spring attachment location between $r - d_s/2$ and $r + d_s/2$ can be calculated as:

$$F = K_s(p + \delta X) - K_s(p - \delta X) = 2K_s\delta X = 2K_s\tilde{r}\sin\delta\theta \tag{1}$$

where $r - d_s/2 \leq \tilde{r} \leq r + d_s/2$

The resultant torque is the cross produce of this force by the projected arm $\tilde{r}\cos\delta\theta$:

$$T = F\tilde{r} = 2K_s\tilde{r}^2\sin\delta\theta\cos\delta\theta \tag{2}$$

The overall torque is the sum of torques over the affecting range d_s:

$$T = \frac{1}{d_s}\int_{r-d_s/2}^{r+d_s/2} 2K_s\tilde{r}^2\sin\delta\theta\cos\delta\theta\, d\tilde{r} = 2K_s\left(r^2 + \frac{d_s^2}{12}\right)\sin\delta\theta\cos\delta\theta \tag{3}$$

The stiffness of the mechanism can be computed by differentiating the torque with respect to the angular deflection:

$$K = 2K_s\left(r^2 + \frac{d_s^2}{12}\right)(2\cos^2\delta\theta - 1) \tag{4}$$

The required forced to change the stiffness supplied by M2 has to overcome projected of the resultant force due to spring's deflection on the direction along the intermediate link:

$$F_{M2} = F\sin(\theta) = 2kr\, sin^2(\theta) \tag{5}$$

Therefore the required energy to change the stiffness is:

$$E_{M2} = \int F_{M2}dr = kr^2\, sin^2(\theta) \tag{6}$$

C. Influence of Design Variables

To permit a certain range of stiffness regulation in this mechanism, spring's rate K_s and the length of the arm r are essential parameters. Using stiffer springs allows reaching a certain level of maximum stiffness with a smaller length of the arm. However, since springs are installed with a pre-compression, internal stress increases requiring stronger structure and more powerful motor to change the stiffness. On the other hand, using softer springs decreases the lower bound for the stiffness and allows using lighter structure and smaller motor to change the stiffness but the arm length should increase to reach a certain maximum value of the stiffness which leads to size increment. Therefore a proper trade off based on the application of this actuator should be made to choose these parameters. Figs. 3 and 4 show how stiffness is affected by choosing different values for these parameters. Fig. 3 shows the stiffness versus the arm for different spring's rate and Fig. 4 shows stiffness versus spring's rate for different arm's length.

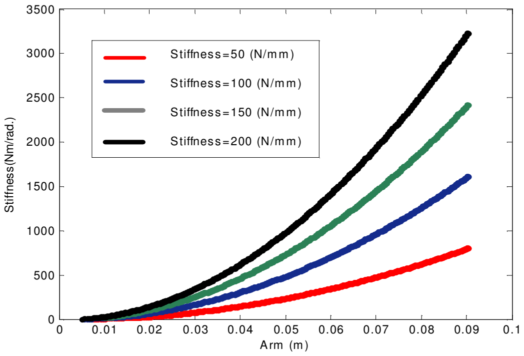

Fig. 3. Effect of arm length on the stiffness for different value of the spring's rate

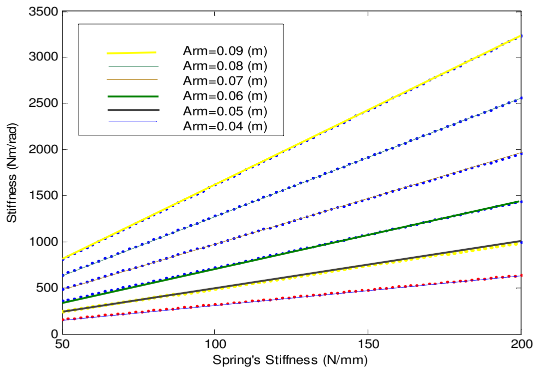

Fig. 4. Effect of spring's rate on the stiffness for different values of the arm length

For the realization of the first prototype the maximum length of the arm and the spring rate were set as 0.09m and 80N/mm, respectively which resulted in a good compromise between achievable stiffness range and actuator size.

Fig. 5 shows the stiffness of our prototype actuator as a function of the arm and angular deflection. As it can be seen the stiffness primary depends on the arm length, with the effect of angular deflection becoming more obvious as the lever arm length increases.

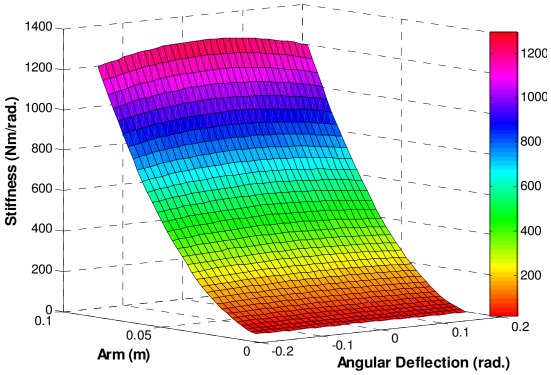

Fig. 5. Stiffness as a function of arm and angular deflection

Fig. 6 shows energy consumption of M2 to change the stiffness from its minimum to maximum under different angular deflections.

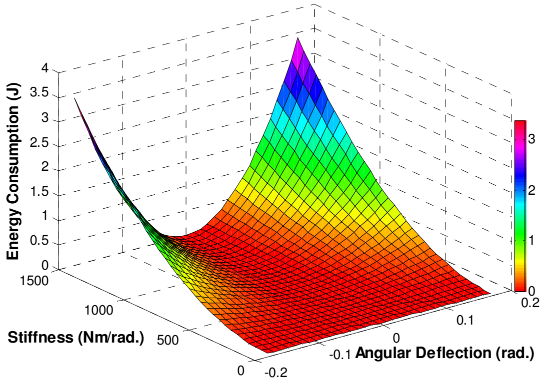

Fig. 6. Energy consumption of M2 to change the stiffness

As it is clear from the graph, the required energy is minimum when the link is close to its equilibrium position.

III. AwAS: MECHANICAL REALIZATION

As it has been mentioned before, AwAS has two motors; one to generate the motion M1 and a second one to tune the stiffness M2. M1 is a brushless frameless DC motor by Emoteq which has a peak torque of 2.35 Nm. As it is shown in Fig. 7, M1 is coupled with a harmonic reduction drive gear box with a ratio of 50:1. The output of harmonic drive is then connected to the intermediate link.

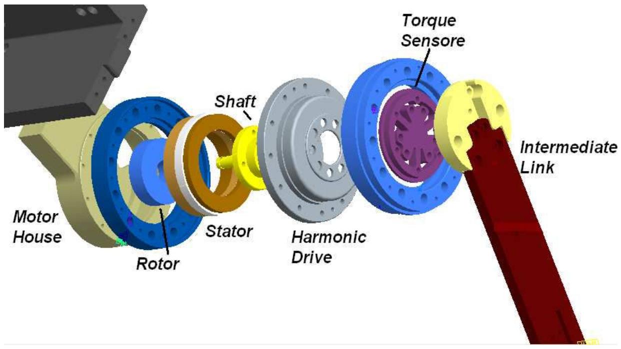

Fig. 7. Exploded view of M1, Harmonic drive and intermediate link

The motor M2 is a DC motor (2.25W) from Faulhaber which is assembled on the intermediate link. The output of M2 is coupled with a ball screw mechanism which converts the rotary motion of M2 into a linear displacement of the ball screw's nut, Figs. 8 and 9.

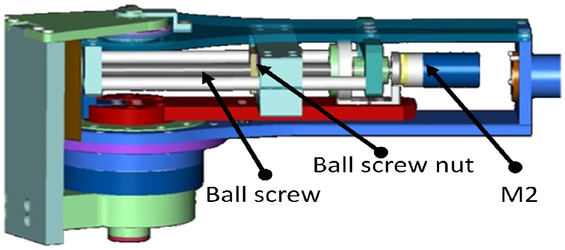

Fig. 8. Side view of AwAS showing the linear drive used for the stiffness adjustment

The two springs are installed with a pre-compression of 6mm which is the half of the spring's maximum deflection. Two linear guides attached on the output link allow springs to travel along the ball screw with low friction. Fig. 10 shows the physical setup of AwAS. A mechanical lock constrains the angular deflection between -0.2 and 0.2 rad. To avoid confusion it is better to notify here that the range of motion is the range in which the link can rotates around its center of rotation with a range of +/-120 degree whereas angular deflection is the angular difference between link and intermediate link which has a range of +/-0.2rad.

The sensing system of AwAS includes four position sensors and one torque sensor; one optical encoder measures the position of the motor M1, two absolute magnetic encoders measure position of the output link and the intermediate link while an incremental encoder monitors the position of motor M2 and subsequently the displacement of the liner drive. The torque sensor is located between the harmonic drive and the intermediate link and sense the torque applied by the main motor of the joint M1. The general specifications of AwAS are presented in Table 1.

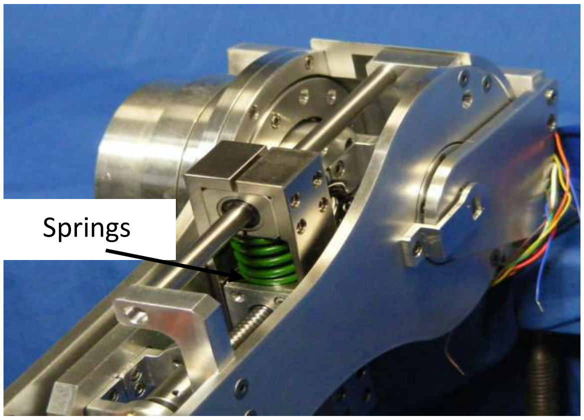

Fig. 9. Placement of the springs

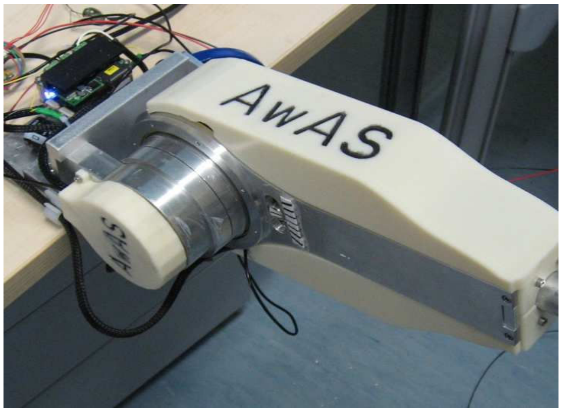

Fig. 10. Physical covered setup of AwAS

Table 1. General Specification of AwAS

Range of Motion (deg)	-120°~120°
Range of Stiffness (Nm/rad.)	30~1300
Peak Output Torque (N)	80
Length (m)	0.27
Width (m)	0.13
Total Weight (Kg)	1.8

IV. EXPERIMENTAL TRIALS

Experiments were conducted to evaluate the performance of the AwAS while regulating the position and stiffness of the joint.

A. Tuning the Stiffness

Fig. 11 shows experimental (solid lines) and corresponding theoretical (dotted lines) torque and angular deflection trends for different arms. The increase slope of the curves as the lever arm becomes longer reveals the effect of stiffness rise.

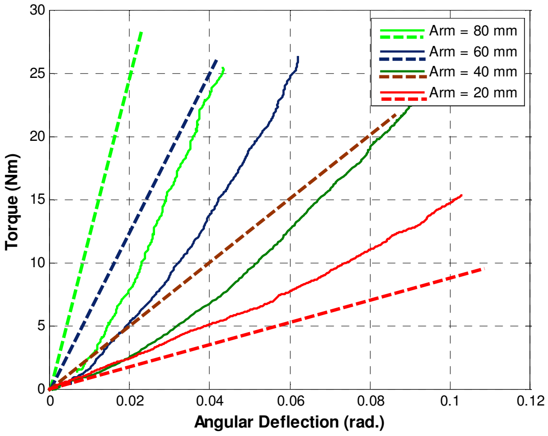

Fig. 11. Torques curves for different arms

Fig. 12 introduces experimental stiffness change step responses from 64 to 250Nm/rad and from 250 to 1024Nm/rad.

It can be observed the capability of the stiffness regulation drive to tune the stiffness with good fidelity. Although step inputs commands are shown in Fig. 12, the controller of the motor M2 was fed with a reference trajectory generated by a minimum jerk trajectory module.

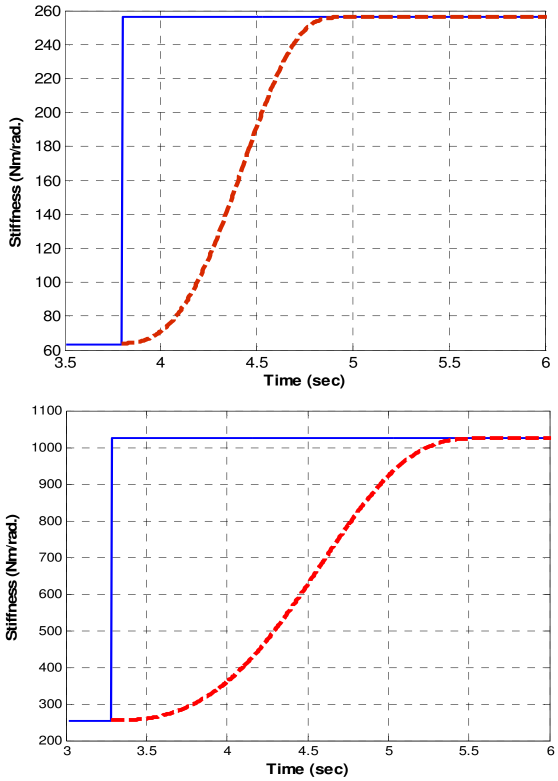

Fig. 12. Stiffness response from 64 to 250 Nm/rad (top) and from 250 to 1024 Nm/rad (bottom)

B. Tracking a Trajectory

In this experiment, both motors M1 for position and M2 for stiffness were simultaneously controlled to follow sinusoidal position and stiffness trajectories of different frequency. Fig. 13 presents the output link position and stiffness trajectories (based on the M2's position trajectory) against the reference ones revealing the capability of the actuator to control both variables independently with good fidelity.

V. CONCLUSION AND FUTURE WORK

In this paper a new actuator with adjustable stiffness AwAS was presented. AwAS is capable of controlling the position and the stiffness of a joint independently. The proposed actuator is capable of regulating the stiffness of the joint in a wide range with a minimum energy consumption by means of a small motor due to its novel mechanical configuration which achieves the stiffness regulation not through the control of the spring pretension (as in most of the existing variable stiffness joints) but by controlling the fixation location of the spring elements. Future work will focus on the use of the actuator to optimimize the energy consumption of the joint during the execution of periodic trajectories thorough appropriate tuning of the stiffness. AwAS will finally be adapted to form an exoskeleton orthosis for the knee joint.

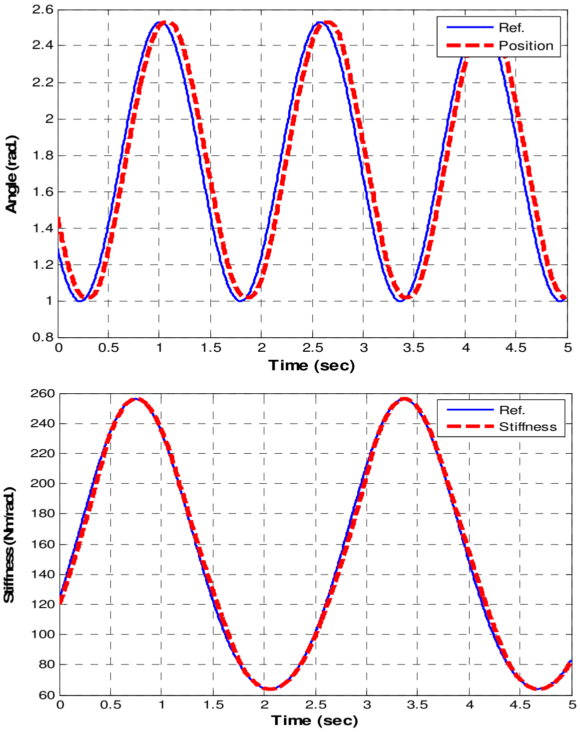

Fig. 13. Tracking a sine wave trajectory; Position (top) and Stiffness (down)

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