

ROTARY ELASTIC COUPLING, ACTUATOR AND CONTROL METHOD

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims benefits from U.S. Provisional Patent Application No. 60/435,992 filed December 23, 2002.

FIELD OF THE INVENTION

The present invention relates generally to electro-mechanical actuators and couplings, and more particularly to a rotary elastic actuator, coupling and associated methods.

BACKGROUND OF THE INVENTION

Existing robotic systems are very successful at performing tasks that only require movement in free space or in known environments under position control. In robotic systems, an ideal actuator for position control of, for example an end effector, is one which is inherently light weight, compact, low cost, stable to control, high power and capable of torque generation. Actuators that are light and compact will not overburden the design constraints of a system. The optimally light and compact actuator will provide a robotic system where movement is easier to control and less power is needed to actuate the system.

As development in robotics continues to progress, conventional position control systems have been found to be inadequate. Known position controlled actuators are somewhat rigid and actuate the robot to a certain position, regardless of the torque/force the system outputs.

By contrast, an actuator that is force sensitive will also actuate the robot to a precise position, but a known force is generated during the actuation. This facilitates a more favorable interaction between the robotic system and the work environment. Indeed, force control is preferred over position control in actuators, particularly those employed in robotic systems.

Traditionally, force controls are just simply force sensors installed in the end-effector which provide a force feedback. Although these actuators are capable of force control, they are still too rigid in certain applications, such as for example, where there is an impact force between the end-effector and a working surface. The impact force can sometimes overload the transmission system. Furthermore, upon impact, the robotic system might vibrate and cause uneven force distribution at the end-effector, which results in an unsatisfactory control system.

Elastic actuators can be useful when employed in robotic systems, as well as in other applications. Elastic actuators include an elastic element such as a spring disposed between the actuator driving end and the driven end. Of particular benefit to robotic systems, elastic actuators can absorb abrupt impacts resulting from a load impact or surface contact, thus increasing the stability of the actuator, while reducing vibration and providing some shielding from possible damage to the actuator.

In conventional elastic actuators, the movements are typically linear, or in rotational movements, they are limited to less than a complete revolution, due to the actuator configuration.

Unlike elastic linear actuators, few elastic rotary actuators have been developed and used, likely due to the drawbacks in conventional elastic rotary actuators. In known elastic rotary actuators, a torsional spring is used to elastically transmit a torque from the driving end to the driven end. However, such a torsional spring is difficult to design and expensive to manufacture. In

many cases, suitable torsional springs are not commercially available and have to be custom-made. Moreover, the rotatable range of the actuator is typically limited due to the required stiffness of the torsional spring. Further, conventional elastic rotary actuators use force or torque feedback for controlling and are not suitable for position control. As well, force feedback is typically sensed in known elastic rotary actuators by measuring the twist in the torsional spring such as with a strain gauge. Such a measurement is difficult and noise prone. The use of a strain gauge may also pose limitations on the spring's operating range because of wiring requirements.

Thus, there is a need for an improved elastic rotary actuator, coupling and control method particularly for an elastic rotary actuator that can be used in a robotic system.

SUMMARY OF THE INVENTION

An rotary elastic actuator includes a rotary elastic coupling having two flywheels coupled by linear extension springs. The flywheels may be used as torque sensors. By measuring the relative angular position between the flywheels, the extension of the springs can be calculated and the overall torque that is being transmitted through the coupling can be computed and controlled. Preferably, encoders are used to measure angular position instead of strain gauges or potentiometers, which are very noise prone. Conveniently, the elastic flywheels permit accurate output torque, and serve as shock absorbers. Thus, impact force transmitted to the motor may be greatly reduced and stored in the springs as potential energy.

Conveniently, as different applications may require different specified performance criteria, the elastic flywheels accommodate different spring stiffness, which in turn make up the overall stiffness of the actuator. Since the extension springs are conventional they are readily available in a variety of

stiffness.

In accordance with an aspect of the present invention, there is provided a rotary elastic actuator includes first and second flywheels mounted about an axis for rotation relative to each other; a pair of linear elastic elements, each having opposing ends. One of the opposing ends of each of the linear elastic elements is mounted to the first flywheel; while the other one of the opposing ends of each of the linear elastic elements mounted to the second flywheel. The pair of linear elastic elements are mounted to bias the first and second flywheels towards an angular equilibrium position relative to each other about the axis of rotation and to exert a net torque about the axis and toward the position of equilibrium, as the flywheels are rotated angular distances in either direction away from the angular equilibrium position.

The actuator may further include a motor operatively connected to the first flywheel for rotating the first flywheel; and a sensor for generating signals indicative of angular positions of the first and second flywheels. A controller may then be operatively connected to the motor and the sensor for controlling the output of the motor based on the signals.

An exemplary method of controlling this actuator includes measuring relative angular displacement between the first and second flywheels and controlling the motor based on the measured angular displacement.

Other aspects and features of the present invention will become apparent to those of ordinary skill in the art upon review of the following description of specific embodiments of the invention in conjunction with the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

In the figures which illustrate by way of example only, embodiments of the present invention,

FIG. 1 is a schematic block diagram of a rotary elastic actuator, exemplary of an embodiment of the present invention;

FIG. 2A is a perspective view of the actuator of **FIG. 1**;

FIG. 2B is an exploded perspective view of the actuator of **FIG. 2A**;

FIG. 3A is a perspective view of the elastic coupling of the actuator of **FIG. 1**;

FIG. 3B is an exploded perspective view of the elastic coupling of **FIG. 3A**;

FIG. 3C is a perspective view of a portion of the elastic coupling of **FIGS. 3A** and **3B**;

FIG. 4A is an enlarged perspective view of a portion of the elastic coupling of **FIG. 3A** and **3B**;

FIG. 4B is an exploded perspective view of the portion shown in **FIG. 4A**;

FIG. 5A is a perspective view of the shafts of the actuator of **FIG. 1**;

FIG. 5B is an exploded perspective view of **FIG. 5A**;

FIG. 6 is a schematic diagram of an elastic coupling, exemplary of an embodiment of the present invention.

FIG. 7 shows the dependence of output torque on relative angular positions of flywheels of the coupling of **FIGS. 3A-3C** for four different springs;

FIG. 8 is a schematic diagram of a control model of the actuator of **FIG. 1**;

FIG. 9 is a block diagram illustrating a control logic for controlling the actuator of **FIG. 1**;

FIG. 11 is a block diagram illustrating alternate control logic for the

actuator of FIG. 1;

FIG. 12 is a block diagram illustrating an alternate control logic for the actuator of FIG. 1;

FIG. 13A-13B show performance comparison of the actuator of **FIG. 1** under different control logic and position control; and

FIG. 14A-14B show the response of the actuator of **FIG. 1** under torque control.

DETAILED DESCRIPTION

FIG. 1 is a simplified schematic block diagram of a controlled rotary elastic actuator **100**, exemplary of an embodiment of the present invention. Actuator **100** has a drive section **200** providing a source of torque for actuator **100**, and a driven load section **300** having a rotational load **302**. An elastic coupling **400** is interposed between drive section **200** and load section **300**, and couples drive section **200** to driven load section **300** to transmit torque and load between drive section **200** and driven load section **300**.

Although not shown in **FIG. 1**, elastic coupling **400** has a motor flywheel interconnected to the drive section, which is positioned opposite an output flywheel that is interconnected to the driven load section **300**. Encoders **206** and **304** are provided to sense the angular positions of the motor flywheel and output flywheel respectively. Encoder **206** and **304** can be formed in any suitable manner known to a person skilled in the art. For example, an encoder **206**, **304** may include an optical position sensor for sensing the positions of a rotating part such as input shaft **434** (or the drive shaft of motor **202**) or output shaft **436**.

An electronic controller **500**, takes as inputs the outputs of encoders **206** and **304**, and is able to control the position of the output shaft and torque

produced by the output of drive section **200**, and is adapted to thereby control the position of, and torque delivered to, the driven load section **300**, as will be explained in detail hereinafter.

FIGS. 2A and 2B illustrate a mechanical embodiment of actuator **100**. For ease of illustration, controller **500** is not illustrated. As illustrated, drive section **200** includes an electric motor **202** coupled to an optional gear box **204**, for generating an input torque about a longitudinal axis of rotation (the *x* axis) of the drive shaft **214** of drive section **200**. As shown in FIG. 2B, gearbox **204** includes a gear head **208**, a main portion **210**, and a coupler **212**. Gearbox **204** is mounted on a gearbox mount **216**. Coupler **212** couples the torsional motion from drive section **200**, to elastic coupling **400** through input drive shaft **434**, which is fixedly attached to and rotates with the motor flywheel **402a** of coupling **400**. Coupler **212** accommodates any axial misalignment between the output shaft **214** from the motor and the input shaft **434** of elastic coupling **400**. Gearbox **204** allows for the conversion of a high speed motor output from motor **202** to a high torque, low speed output. As will become apparent, this facilitates the easier control of the output speed and torque.

Drive section **200** and its components are preferably reversible, low-friction and have low backlash transmission. In some applications, they should be made of light material. Preferably motor **202** has high torque to current ratio and is relative compact in size and commercially available. For example, in one embodiment, motor **202** may be formed as a 400 watt Panasonic servo motor. Encoders **206** and **304** may be conventional 2500 pulse per revolution encoders. Gear box **204** may be a ZF 40:1 gear head, and coupler **212** may be a 3 beam Huco™ coupler. As is known, the Huco coupler has high torsional rigidity, zero backlash, no moving parts and can accommodate certain misalignment of the motor drive shaft **214**.

Also as illustrated in **FIG. 2B**, driven load section **300** includes a bearing housing **306** that is coupled to an output shaft **436** from coupling **400**. Output

shaft **436** is fixedly attached for rotation with output flywheel **402b**. Load **302** is fixedly mounted on housing **306** to output shaft **436**. Housing **306** supports load **302** and constrains its motion to single axis rotation about the **x** axis. Driven load section **300** also includes encoder mount **310** for mounting an encoder bearing **312** and encoder **304**. As illustrated, load **302** is depicted as a static mass with weight **m**. In practice, load **302** may be a variety of loads such as for example a robot arm, or the like.

Elastic coupling **400** includes an input flywheel **402a** and an output flywheel **402b** (collectively referred to as flywheels **402**). In this embodiment, flywheels **402a** and **402b** are mounted for rotation about a common axis **x** in opposed, proximate but spaced relation to each other. A plurality of linear springs **404**, are positioned between the flywheels **402a** and **402b** toward their outer peripheral edges. Linear springs **404** interconnect flywheels **402a** and **402b** to each other and are adapted to be capable of elastically transmitting an input torque from input flywheel **402a** to output flywheel **402b**.

As best illustrated in **FIGS. 3A, 3B** and **4**, in this embodiment springs **404** are arranged in pairs, in this case there being four pairs of springs. One spring **404a** of each pair is arranged adjacent to the other spring of the pair **404b**, around the periphery of the circumference. The positioning of four pairs of springs **404a, 404b** ensures that a steady equilibrium position can be established between the drive section **200** and load section **300** (**FIGS. 2A** and **2B**), when no load is being applied through coupling **400**.

It should be noted that various other linear spring arrangements are possible. For example, a single pair of springs could be interconnected between flywheel **402a** and flywheel **402b**, one of the pair of springs being positioned generally 180 degrees opposite to the other of the pair about axis **x**. The interconnection to the flywheels **402a, 402b** can be configured so that one spring exerts torques on each flywheel in one direction (but opposite for each flywheel) and the other spring exerts torques on each flywheel in an opposite direction.

The result is that each flywheel has two springs, each exerting torque in an opposite direction on it. A resultant equilibrium position can thus be established.

Generally, however, more than one set of pairs of springs is preferred to provide relatively larger combined spring stiffness for elastic coupling **400**.

Each spring **404** has two opposing ends **406**. Each end **406** includes a loop (as best illustrated in **FIG. 3C**) for mounting to one of flywheels **402**. One end (**406a**) of each spring **404** is mounted on input flywheel **402a** and the opposing end (**406b**) of the spring is mounted on output flywheel **402b**. Flywheels **402** are axially spaced so that springs **404** are disposed between flywheels **402a**, **402b** generally in a plane perpendicular to the axis of rotation.

As illustrated in **FIG. 3B**, each flywheel **402** includes four sliders **410** mounted at equally spaced angular positions about its axis of rotation. Springs **404** are secured on sliders **410**, as more particularly illustrated in **FIGS. 4A** and **4B**. On one end of each slider **410** there are two threaded openings **412** for receiving connecting bolts **414**. An end of a spring **404** is secured to a slider **410** by a connecting bolt **414** threaded to the slider through the hole of its head and a cover plate **416**. To allow spring **404** to rotate smoothly about the connecting bolt **414**, a ceramic bushing **418** can be inserted between the spring head and the screw. Slider **410** includes a hole **420** for receiving an adjusting bolt or rod **422** and grooves **424** for engaging a rail on the flywheel.

Four adjusting bolt or rods **422** are mounted on each flywheel **402**. Threaded rods **422** are spaced about 90 degrees apart around the flywheels and extend radially outwards from the centre hub portion of the flywheels **402**, as illustrated in **FIGS. 3A** and **3B**. Sliders **410** can be moved radially outward and inward along their respective adjusting rods **422** during assembly to adjust and set the extended lengths of springs **404**. Flywheels **402** have guiding rails **426** for engaging grooves **424** and assisting the movement of guiding sliders **410** radially inward and outward. During operation of the actuator, sliders **410** are fixedly

secured at set radial positions on rods **422** to flywheel **410** by set screws **428** that pass through threaded opening **430**, to engage the surface of rails **426**, to lock the sliders in position. Sliders **410** are generally circumferentially disposed so that each spring is disposed with its lengthwise extent tangential to a direction of rotation about the axis. However, the orientation of the lengthwise direction of the spring can in some embodiments be varied somewhat from the tangential orientation.

Around the circumference of the flywheels **402**, adjacent springs are mounted such that their ends **406a** are angularly adjacent to each other and the opposite ends **406b** are angularly adjacent to each other. In other words, the adjacent ends of two adjacent springs are always mounted on the same flywheel **402**. The mounting arrangement is best shown in **FIG. 3C**. Further, with all of springs **404** mounted, the sliders **410** can be positioned so that each spring **404** is extended midway between its natural length and its full elastically extendable length when the flywheels **402** are in their equilibrium position. Therefore, each spring is partially elastically deformed and biases the flywheels **402** away from their equilibrium position. However, since four of the eight springs **404** (the ones marked as **404a**) bias the flywheels away from the equilibrium position in one rotational direction and the other four of the eight springs **404** (the ones marked as **404b**) bias the flywheels away from the equilibrium position in another direction of rotation, and the magnitudes of the two opposing torques are equal, the flywheels **404** establishes an equilibrium position with no net torque being exerted on either flywheel, when there is no external torque or load is applied.

In the depicted embodiment, all springs **404** have the same natural length and stiffness. However, springs **404** may have different lengths and/or stiffness. As can be appreciated, initially extending each spring to half of its elastically extendable length is advantageous because the stiffness of the elastic coupling as a whole is consistent and the flywheels **402** can relatively rotate in both directions of rotations. It is possible, however, to partially deform the springs to

different extents in certain applications, such as when the torque ranges required for the two rotation directions are different. Further, when the torque ranges are different, springs **404a** and **404b** may have different stiffness.

Springs **404** may be any suitable springs including coil springs and the like. The elasticity (i.e. spring constant) of springs **404** can be determined from the required torque range as is understood by a person skilled in the art. Springs **404** can also be replaced with other linear elastic couplings such as elastic bands and the like.

As used herein, linear elastic means that the spring or other elastic element behaves elastically when deformed in a linear direction. This does not however, necessarily mean that the elastic deformation will behave linearly according to Hooke's law.

As further illustrated in **FIGS. 3A, 3B, 3C, 5A and 5B**, rotary elastic coupling **400** includes a hub **432** connected to input shaft **434** from drive section **200** coupled to coupler **212** of drive section **200** and an output shaft **436** coupled to mounting housing **308** (**FIG. 2A**) and load **302** of load section **300**. Hub **432** includes a centring shaft **446** extending from shaft **434**. Output shaft **436** has a bore **444** for receiving a portion of centring shaft **446**. Hub **432** also includes ball bearing **450**, thrust bearing **452**, flange **454** and spacers **456**. As can be understood, flanges **454** and **456** keep flywheels **402a** and **402b** at a constant axial distance while bearings **450**, **452** reduce rotational friction between rotating parts of elastic coupling **400**. When assembled, shafts **434** and **436** are generally co-axial and can rotate about the centring shaft and hence the common x-axis relative to each other. This arrangement ensures alignment of shafts **434** and **436** and their reliable and smooth rotation.

Flywheel **402a** is fixedly attached to shaft **434** for rotation therewith, and flywheel **402b** is fixed coupled to output shaft **436** for rotation therewith. The end of input shaft **434** facing the output shaft **436** has a flange **440**. Flange **440** has

four bolt holes for securing input flywheel to shaft **434**. Similarly, the end of output shaft **436** facing the input shaft **434** has a flange **442**. Flange **442** also has four bolt holes for securing output flywheel to output shaft **436**. A plurality of spaced lugs **456** extend in an axial direction from each of flanges **440** and **442**.

Controller **500** illustrated in **FIG. 1**, may be a conventional industrial programmable controller that takes as inputs current or voltage signals from encoders **206** and **304**, and provides one or more output signals controlling the position or torque of motor **202** and hence shaft **434**. Controller **500** may, for example, be an Intel x-86 based computing device including a Servo Togo peripheral card. Controller **500** is programmed with control software loaded from computer readable medium. As detailed below, controller **500** is programmed to apply a constant torque to load **302**. As will become apparent, a constant applied torque allows smooth and quick movement of load **302**, as may be required in robot applications.

In operation, in the absence of an external applied torque at the output flywheel **402b**, the two flywheels **402a** and **402b** are in an equilibrium angular position relative to each other. To rotationally move a load **302** or to overcome an external load, motor **202** produces a torque which is transmitted through gearbox **204** to elastic coupling **400** causing the input shaft **434** and hence input flywheel **402a** to rotate. Because springs **404** are elastic and input and output shafts can rotate relative to each other, and because output flywheel **402b** is carrying load **302**, flywheel **402a** will rotate relative to flywheel **402b** away from the equilibrium position.

As such, one spring of each pair of adjacent springs **404a**, **404b** is further stretched and the other of each pair shortened. Thus, the forces exerted by the groups of pairs springs in a direction tangent to the axis of rotation no longer are in balance, and the net torque produced by springs **404** causes flywheel **402b** to rotate and follow flywheel **402a**.

At the same time, if flywheel **402b** or load **302** is subject to a sudden external force (e.g. a shock) about the axis of rotation, the force may at least to some extent be absorbed or dampened by springs **404**. As such, the external force will be less likely to cause damage to the drive end **200**, including gearbox **204** and the motor **202**. Thus, actuator **100** is compliant, shock resistant and yet stable.

In the event torque is applied too quickly, lugs **456** on flange **440** may drag lugs **456** on flange **442**, thereby mitigating damage to coupling **400**.

The net torque exerted by springs **404** on flywheel **402b** can be readily calculated by monitoring the relative angular position $\Delta\theta$ of flywheels **402**. Encoders **206** and **304** can be used to generate signals indicative of the relative angular positions of input and output shafts **434** and **438**, and provide these to controller **500**. Controller can, in turn, calculate the net torque and control operation of motor **202** to provide constant torque using control techniques appreciated by those of ordinary skill.

An exemplary torque calculation is illustrated below with reference to **FIG. 7**. For simplicity only four springs are illustrated in **FIG. 7**. As can be understood, the principles illustrated here are equally applicable with eight or any other number of springs. For simplicity, it is assumed that there is no friction between any of the rotational parts of actuator **100**.

The following parameters are known or measurable:

radius R , the distance between the end of each spring to the x-axis, which is the same for all springs in this case;

number of springs, n ;

natural (or free) length of each spring, L_0 , (assumed to be the same for all springs in this case;

spring constant K_s of each spring,

angle α between the two ends of two adjacent springs mounted on one slider **410**;

relative angular displacement $\Delta\theta$ of the two flywheels **402a** and **402b** from their angular equilibrium position.

Further, in the example calculations flywheels **402** are assumed to be displaced so that springs **404a** are further extended and springs **404b** are compressed. Thus, the forces exerted by each spring **404a** or **404b** may respectively be approximated as:

$$F_a = K_s (L_a - L_0) = K_s \{2 [R/\cos(\alpha)] \times \sin[(\pi/n)-\alpha - (\Delta\theta / 2)] - L_0\}$$

$$F_b = K_s (L_b - L_0) = K_s \{2 [R/\cos(\alpha)] \times \sin[(\pi/n)-\alpha + (\Delta\theta / 2)] - L_0\}$$

The resulting torque about the x axis produced by each spring is respectively:

$$\tau_a = F_a \times R \times \cos[(\pi/n)-\alpha - (\Delta\theta / 2)] \times \cos(\alpha)$$

$$\tau_b = F_b \times R \times \cos[(\pi/n)-\alpha + (\Delta\theta / 2)] \times \cos(\alpha)$$

Thus, the net total torque about the x axis produced by all springs is:

$$T = (n/2) \times (\tau_b - \tau_a)$$

FIG. 8 illustrates the dependence of the transferred output torque on the angular displacement $\Delta\theta$ between the flywheels **402a** and **402b** of actuator **100** for four different types of linear springs. As can be seen, the dependence is generally linear.

Thus, elastic coupling **400** may be modelled as a rotary elastic actuator having a single compound spring constant. The output torque can approximated

as being a linear function of the angular displacement of the two flywheels **402** and the compound spring constant (i.e., $T = K_{\text{coupling}} \times \Delta\theta$). K_{coupling} may be approximated mathematically or by experiment.

A simple schematic model of actuator **100**, used for its control under controller **500**, is shown in **FIG. 9**. τ_M is the torque at the output of motor **202**, J_m the moment of inertia of motor **202**, K_{coupling} is the spring constant of elastic coupling **400**, τ_L the output torque from coupling **400**, θ_M and θ_L are respectively the angular position of flywheels **402a** and **402b** about the x axis, m the mass of load **302** and l is the position of the centre of gravity of load **302** from the rotation axis x

FIG. 9 is a block diagram illustrating control logic **502** used in controller **500** for controlling actuator **100** to apply a constant torque. Control logic **502** may be included in controller **500** using conventional programming techniques. Controller **500** estimates the torque (τ_m) to be applied by actuator **100** as a function of sensed angular displacements $\Delta\theta$ between flywheel **402a** and **402b**. Specifically, controller **500** estimates τ_m , as

$$\tau_m = \alpha\tau' + \beta,$$

$$\text{where } \tau' = \ddot{\theta} = -K_p\Delta\theta - K_v\dot{\Delta\theta},$$

$$\alpha = J_m + ml^2$$

$$\beta = mgl \sin \theta$$

As can be understood, α is the rotational inertial mass of actuator **100** due to motor mass and the load mass; τ' is the calculated torque, as a function of angular displacement, β is the torque generated by gravity, $K_p = K_{\text{coupling}}$ is the spring constant for the elastic coupling **400** and K_v is a damping factor for the elastic coupling **400**

In this control circuit, the feedback controller **500** uses the angular position

difference between the input and output flywheels **402** ($\Delta\theta$) and the angular velocity ($\dot{\theta}$), i.e., the rate of change of the difference to account for damping of springs **404**. The feedback controller **500** also uses the angular position of the output flywheels **402b** (θ_b) and the angular velocity of the output flywheels **402b** ($\dot{\theta}_b$) to compute a motor torque. The computed torque is used in the control algorithm for controlling the position of motor **202**.

FIG. 10 is a block diagram illustrating alternate control logic **502'** that may be used by controller **500** of actuator **100**. Logic **502'** includes an inner Proportional-Integration-Derivation (PID) control block **504**. Controller **500** using control logic **502'** computes a torque based on the angular position of the output flywheels **402b** (θ_b) and the angular velocity of the output flywheels **402b**. This torque is further regulated with inner loop PID torque control **504** based on the output torque, τ_L as shown below:

$$\tau_m = \frac{K_p s + K_D s^2 + K_I}{s} (\tau - \tau_L)$$

where s is the Laplace transform variable; K_p is the Proportional gain, K_i is the Integral gain, and K_d is the derivative gain of PID control block **504**. Suitable values for P, I, and D may be calculated or approximated using simulation software and adjusted. For example these may be obtained using a SimuLink Simulation and then verified by manual tuning.

FIG. 11 is a block diagram of further alternate control logic **502''** for controller **500** controlling actuator **100** under PID torque control. Desired torque is compared with the output torque and regulated using a PID controller to send a signal to the motor amplifier, which in turn sends an appropriate current to the motor until the desired torque is achieved.

FIG. 12A and **12B** illustrated measures performance of the actuator **100**

under position control using controller **500**, programmed using blocks **502** and **502'** (FIGS. **10** and **11**). As illustrated, actuator **100** has improved performance with the inner loop torque PID control (i.e. control blocks **502'** - FIG. **11**) over the performance without the inner loop torque control (i.e. control blocks **502** – FIG. **10**), although the improvement under trajectory control is less than that under step positioning. As can be understood, inner loop PID torque control senses actual torques (τ_L). In this measurement, the flywheels **402** together with encoders **206** and **304** are used to estimate torque through coupling **400** and provide torque feedback for the controller. As can be seen, for given controller gains, an actuator with inner loop torque PID control is capable of positioning itself more accurately, due to corrections for friction present in the system. Controller **500** modulates a torque at the output shaft **436**, which is as close as possible to the torque commanded by the controller **500**. By doing so, errors such as friction and damping in the system are compensated.

FIG. 13A and **13B** compare the measured and simulated performance of actuator **100** using control blocks **502'** with output shaft **436** clamped. The results show that actuator **100** can be accurately and stably controlled even under low controller gains. To achieve faster response to a desired torque, controller gains can be increased.

As can be appreciated, exemplary elastic rotary actuator **100** has many advantages. For example, the linear springs **404** used in rotary elastic coupling **400** can be easily designed and manufactured. In many situations, suitable springs will be commercially available. The rotatable range of the actuator can be large because the stiffness of suitable linear springs can vary widely and because it is not necessary to attach any gauge or sensor to the springs. Further, as illustrated, it is possible to control the actuator using positional control and position feedback. It is relative easy to sense the angular positions of the rotating shafts or the input/output flywheels.

Of course, the above described embodiments are intended to be

illustrative only and in no way limiting. The described embodiments of carrying out the invention are susceptible to many modifications of form, arrangement of parts, details and order of operation. The invention, rather, is intended to encompass all such modification within its scope, as defined by the claims.

CLAIMS:

1. A rotary elastic actuator comprising:

first and second flywheels, mounted about an axis for rotation relative to each other;

a pair of linear elastic elements, each having opposing ends, one of said opposing ends of each of said linear elastic elements mounted to said first flywheel; the other one of said opposing ends of each of said linear elastic elements mounted to said second flywheel;

said pair of linear elastic elements mounted to bias said first and second flywheels towards an angular equilibrium position relative to each other about said axis of rotation and to exert a net torque about said axis and toward said position of equilibrium, as said flywheelss are rotated angular distances in either direction away from said angular equilibrium position.

2. The actuator of claim 1, further comprising a motor operatively connected to said first flywheel for rotating said first flywheel.

3. The actuator of claim 2, further comprising a sensor for generating signals indicative of angular positions of said first and second flywheels, and a controller operatively connected to said motor and said sensor for controlling the output of said motor based on said signals.

4. The actuator of any one of claims 1 to 3, further comprising additional pairs of linear elastic elements.

5. The actuator of any one of claims 1 to 4, wherein each one of said linear elastic elements is a linear spring.

6. The actuator of claim 5, wherein said linear springs are all of the same natural length and stiffness.

7. The actuator of claim 6, further comprising additional pairs of linear elastic elements, each of said additional pairs mounted to bias said first and second flywheels towards said angular equilibrium position relative to each other about said axis of rotation and to exert a torque toward said position of equilibrium, as said flywheels are rotated angular distances in either direction away from said angular equilibrium position.
8. The actuator of claim 7, wherein said pair of linear springs and said additional pairs of linear springs are circumferentially disposed about said axis.
9. The actuator of claim 3, wherein said sensor comprises two optical position sensors.
10. The actuator of claim 9, wherein one of said two optical position sensors is disposed to sense the angular position of said second flywheel and the other one of said optical position sensors is disposed to sense the angular position of said first flywheel.
11. The actuator of claim 10, wherein each of said optical position sensors comprises an encoder for converting a sensed angular position into a signal indicative of said sensed angular position.
12. The actuator of claim 10 or claim 11, wherein said motor is controlled to generate a constant torque based on the difference between said angular positions of said first and second flywheels.
13. The actuator of claim 12, wherein said controller comprises an inner loop proportional-integral-derivative (PID) control circuit.
14. The actuator of claim 12, wherein said controller comprises a proportional-integral-derivative control circuit.

15. The actuator of any one of claims **10** to **14**, wherein said controller controls said motor based on a desired output position and said difference between said angular positions.
16. The actuator of any one of claims **10** to **14**, wherein said controller controls said motor based on a desired output torque and said difference between said angular positions.
17. The actuator of claim **15** or **16**, wherein said controller controls said motor based further on a measured output torque computed from said difference between said angular positions.
18. The actuator of claim **16** or **17**, wherein said controller controls said motor based further on a rate of change of said difference between said angular positions.
19. The actuator of any one of claims **10** to **18**, wherein said controller controls said motor exert near constant torque on said second flywheel.
20. The actuator of any one of claims **10** to **19**, wherein said controller controls said motor to rotate said second flywheel to a desired angular position.
21. The actuator of any one of claims **1** to **20**, further comprising a gearbox operatively connected to said motor, and comprising a coupler operatively connected to said gearbox and said first flywheel, said gearbox and coupler capable of transmitting a rotational motion of a drive shaft of said motor to a rotational motion of said first flywheel.
22. The actuator of claim **21**, further comprising an input shaft, said input shaft operatively connected to said coupler and said flywheel so as to transmit a rotational motion of said coupler to a rotational motion of said flywheel.
23. The actuator of claim **22**, further comprising an output shaft, said output shaft operatively connected to said second flywheel and a load to be rotationally

moved so as to transmit a rotational motion of said second flywheel to a rotational motion of said load.

24. The actuator of claim **23**, further comprising a centering shaft, said input and output shafts are rotatably coupled to said centering shaft such that said input and output shafts are axially aligned and rotatable relative to each other.

25. The actuator of claim **1**, wherein each of said first and second flywheel comprises a plurality of sliders mounted on said each flywheel, each end of each one of said elastic elements mounted on one of said sliders, each of said sliders slidable in a radial direction during assembly such that the extended lengths of said elastic elements can be adjusted, said sliders fixed on said each flywheel during use.

26. A rotary elastic actuator comprising:

first and second flywheels, mounted about an axis for rotation relative to each other;

a pair of linear elastic elements, each having opposing ends, one of said opposing ends of each of said linear elastic elements mounted to said first flywheel; the other one of said opposing ends of each of said linear elastic elements mounted to said second flywheel;

said pair of linear elastic elements mounted to bias said first and second flywheels towards an angular equilibrium position relative to each other about said axis of rotation and to exert a net torque about said axis and toward said position of equilibrium, as said flywheels are rotated angular distances in either direction away from said angular equilibrium position;

a motor operatively connected to said first flywheel for rotating said first flywheel;

a sensor for generating signals indicative of angular positions of said first and second flywheels; and

a controller operatively connected to said motor and said sensor for controlling the output of said motor based on said signals.

27. A rotary elastic coupling comprising:

a first rotating member mounted for rotation about an axis of rotation;

a second rotating member mounted about said axis of rotation, said first rotating member being mounted in a generally opposite relation to said second rotating member;

first and second linear elastic elements connected between said first and second rotating members,

said first linear elastic element being connected between said first and second rotating members to exert forces on said first and second rotating members creating a torque transmitted to said first rotating member in a first rotational direction about said axis of rotation, and a torque transmitted to said second rotating member in a second direction opposite to said first direction about said axis of rotation;

said second linear elastic element connected between said first and second rotating members to exert forces on said first and second rotating members creating a torque transmitted to said first rotating member in said second rotational direction about said first axis of rotation, and a torque transmitted to said second rotating member in said first direction about said axis of rotation;

said first and second rotating members being biased towards an equilibrium position relative to each other by said first and second linear elastic elements, and said coupling operable to elastically transmit a load between said first and second rotating member through said first and second linear elastic elements as one of said first and second rotating members is rotated relative to the other of said first and second rotating members, as said load is applied to said one rotating member.

28. A method of controlling torque provided through a rotary elastic actuator, said rotary elastic actuator comprising:

first and second flywheels, mounted about an axis for rotation relative to each other;

a motor coupled to rotate said first flywheel about said axis;

a pair of linear elastic elements, each having opposing ends, one of said opposing ends of each of said linear elastic elements mounted to said first flywheel; the other one of said opposing ends of each of said linear elastic elements mounted to said second flywheel;

said pair of linear elastic elements mounted to bias said first and second flywheels towards an angular equilibrium position relative to each other about said axis of rotation and to exert a net torque about said axis and toward said position of equilibrium, as said flywheels are rotated angular distances in either direction away from said angular equilibrium position;

said method comprising:

measuring relative angular displacement between said first and second flywheels;

controlling said motor based on said measured angular displacement.

29. The method of claim **28**, wherein said controlling further comprises estimating torque provided through said coupling based on said angular displacement.

30. The method of claim **29**, wherein said controlling comprises controlling said motor to provide constant torque.