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A New Mechanical Structure for Adjustable Stiffness Devices with Lightweight and Small Size

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***Abstract*— In this paper, we propose a new mechanical structure for adjustable stiffness devices with lightweight and small size. The proposed structure utilize a ball screw mechanism to adjust a relationship between infinitesimal displacements of joint rotation and a linear spring. Then, stiffness around the joint is adjusted. Unlike many of other adjustable stiffness structures, available elastic energy of the elastic element is maximum when the stiffness of the proposed structure is maximum. Therefore, the elastic element of this structure can be smaller and more lightweight than the other structures. Another advantage of the proposed structure is to require fewer and smaller mechanical parts, because the proposed mechanism mostly requires the ball screw mechanism and the linear spring. We developed an actual hardware to test the proposed structure.**

***Index Terms*— Adjustable Stiffness, New Mechanism, Lightweight, Small**

I. INTRODUCTION

A. Stiffness Adjustment in Scientific and Technology Field

Human beings and animals generate motions dexterously. A lot of factors seem contribute the dexterous motions. Since it has been investigated that human beings and animals move while adjusting stiffness of their muscles and tendons, one of the factors may be utilization of the stiffness adjustment. Therefore, to adjust mechanical stiffness is an interesting issue from the scientific viewpoint.

In the field of robotics, electric motors with high reduction gears have generated motions of robots traditionally. Researchers also have proposed control methods of the robots actuated by such electric motors. Advancements of the electric motors and the control methods have enhanced abilities of the robots. However, capabilities of electric actuators seem to be reaching almost limit, and strong advancements of actuator capabilities may not be expected in the near future. In addition, since some recent robots perform tasks with human, very stiff joints of robots due to the high reduction gears seem not suitable for the recent robots [1]. Therefore, researchers are recently trying to investigate alternative ways to generate robot motions. One of the important alternative ways seems to utilize mechanical elastic elements.

From a viewpoint of energy efficiency, to utilize elastic elements is also effective, because resonance of mechanical systems can save energy while generating periodic motions of the robots.

B. Resonance-based Control Method

We have proposed resonance-based control methods that utilize online stiffness adjustment of mechanical elastic elements installed in each joint of multi-joint robots [2], [3], [4], [5], [6]. The proposed controllers can generate periodic motions of multi-joint robots while minimizing actuator torque by adjusting the stiffness. We have tried to extend the concept of resonance to multi-joint robots [2], [3]. The proposed controllers can guarantee global stability of controlled systems [2]. Not only stiffness adjustment but also motion pattern adjustment reduce actuator torque furthermore [3], [4]. This kind of controller could reduced more than 90[%] of actuator torque for walking motions [5]. Application of the control methods are human walking support systems [6], energy saving industrial manipulators and walking/running robots. Now, we are developing a hardware of a legged robot as shown in **Fig.1**. The robot is aimed at running by using the resonance-based control methods. Therefore, the robot should equip adjustable stiffness devices in every joint of the robot.

However, if we use some structures of adjustable stiffness devices, it may be difficult for the robot to run due to large weight of the adjustable stiffness devices. Therefore, we need adjustable stiffness devices with lightweight and small size that can be installed in joints of multi-joint robots.

C. Related Work on Stiffness Adjustment

In order to develop adjustable stiffness devices, many researchers have proposed mechanical structures [7], [8], [9], [10], [11], [12], [13], [14].

One simple approach for the stiffness adjustment is to vary effective length of elastic elements. For example, effective length of a leaf spring can be adjusted by moving a linear slider [7].

Another approach is to utilize two nonlinear elastic elements [8], [9]. The two nonlinear elastic elements are mounted antagonistically on a joint. Then, by pulling the two elastic elements, stiffness around the joint is adjusted.

Fig. 1. Developing Legged Robot

This structure is similar to that of human beings, because human can adjust their joint stiffness by co-contraction of antagonistic muscles. For this structure, how to make the elastic elements nonlinear becomes a key issue. K. Koganezawa realized the nonlinearity by using rotational springs and tapers [8]. Rotating the rotational springs makes the springs twine around the tapers. Then, the stiffness of the springs depends on the rotated angle of the spring. H. Noborisaka *et al.* realized the nonlinearity by using linear springs and wires [9].

In another approach, varying pretension and preload of elastic elements brings about the stiffness adjustment. This kind of structure requires not two elastic elements but only one elastic elements for a joint. B. Vanderborght *et al.* proposed a simple structure called MACCEPA based on this kind of mechanism [10]. S. Wolf *et al.* also proposed this kind of structure called VS-joint [11].

However, in the case of the above structures, available elastic energy of the elastic elements is minimum, when the stiffness is maximum. Then, we need larger and heavier elastic elements, because storable elastic energy is proportional to weight and size of the elastic elements, and deformable displacement of the elastic elements is proportional to root square of the storable elastic energy. Therefore, if we solve this problem, we can develop smaller and more lightweight adjustable stiffness devices.

Varying relationship between infinitesimal displacements of joint rotation and elastic elements can be a solution of this problem, because available elastic energy of this structure can be maximum even in the case of maximum stiffness. For example, varying a moment arm length of a spring force can adjust the infinitesimal relationship, and stiffness around a joint. Then, no load acting on the spring is required in the case of maximum stiffness. N. Takesue proposed an adjustable stiffness structure utilizing this kind of mechanism [13]. This structure varies a position of one side of linear springs to adjust the infinitesimal relationship. Then, available elastic energy of the linear spring is maximum even in the case of maximum stiffness. However, this structure is designed for translational joints. Therefore, we can not directly use this structure for rotational joints of our legged robot. In addition, to vary the position of one side of the linear spring seems to require large work space. V. Duindam *et al.* illustrated an idea of an adjustable stiffness structure that utilizes the adjustment of the infinitesimal relationship [14]. This structure is composed of a flexible cam and a linear spring. In this case, the infinitesimal relationship is adjusted by varying the shape of the cam. However, this kind of flexible cam seems to be large and heavy, and require large work space. In addition, this structure was stated as just a conceptual idea. Therefore, there were no detailed discussions or concrete analyses, and actual hardware devices were not presented.

Hence, if we can make small devices that vary the infinitesimal relationship, we can develop adjustable stiffness devices with lightweight and small size.

D. This Study

In this paper, we proposed a new mechanical structure that varies a relationship between infinitesimal displacements of joint rotation and a linear spring by using a ball screw mechanism. Then, available elastic energy of the spring is maximum, when stiffness around the joint is maximum. Therefore, the elastic element of the proposed structure can be lightweight and small. Another advantage is that the ball screw mechanism does not require a lot of mechanical parts and large work space. In addition, the stiffness of the proposed structure can be adjusted from 0 to the maximum one theoretically. Therefore, range of the adjustable stiffness can be large.

This paper analyzes some characteristics of the proposed structure. We develop an actual hardware utilizing the proposed structure, and conducted an experiment to test the developed hardware.

II. PROPOSED STRUCTURE

This section describes details of the proposed mechanical structure.

A. Structure

The proposed structure uses a ball screw mechanism and a linear spring as shown in **Fig.2**. The ball screw mechanism is rigidly attached to the rotating shaft, which is rigidly attached to the base link at the joint. The one side of the spring is attached to the fore link. The other side of the spring is attached to the nut of the ball screw mechanism. The length from the joint to the one side of the spring should be longer than the length from the joint to the nut $l > r$. The position of the nut can be adjusted by rotating the screw of the ball screw mechanism. The motor rotates the screw.

B. Principle of Stiffness Adjustment

The principle of the stiffness adjustment is as follows. When we adjust the length from the joint to the nut r by moving the nut position, relationship between infinitesimal displacements of the joint rotation δq and the spring δl_s is varied. Then, rotational stiffness around the joint is adjusted.

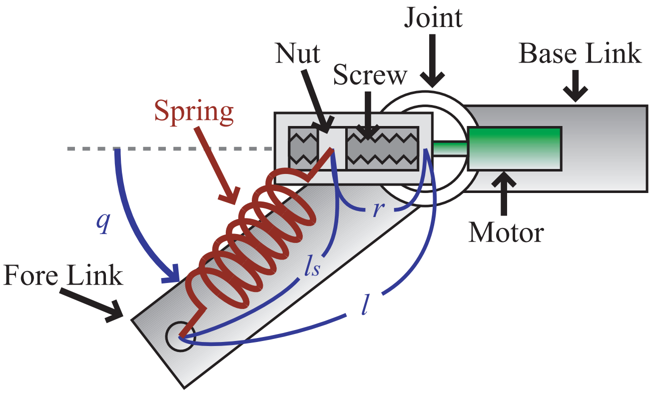

Fig. 2. Proposed Mechanism

C. Mathematical Analysis

Here, we analyze the stiffness around the joint of the proposed structure so as to clarify characteristics of the stiffness adjustment quantitatively,

At first, we calculate the length of the spring $l_s(q)$ as

$$\begin{aligned} l_s(q) &= \sqrt{l^2 \sin^2 q + (l \cos q - r)^2} \\ &= \sqrt{l^2 + r^2 - 2lr \cos q}, \end{aligned} \tag{1}$$

where l is a length from the joint to the one side of the spring attached to the fore link.

Elastic energy U of the linear spring is given by

$$U = \frac{1}{2} k_l (l_s - l_{s0})^2, \tag{2}$$

where k_l is stiffness of the linear spring, and l_{s0} is natural length of the spring.

Torque from the spring around the joint is given by differentiating the elastic energy U with respect to the joint angle q.

$$\tau_s = \frac{\partial U}{\partial q} = k_l lr \left(\sin q - \frac{l_{s0} \sin q}{\sqrt{l^2 + r^2 - 2lr \cos q}} \right) \tag{3}$$

The stiffness around the joint k_q is given by differentiating the torque τ_s with respect to the joint angle q.

$$\begin{aligned} k_q = \frac{\partial \tau_s}{\partial q} &= k_l lr \left(\cos q - \frac{l_{s0} \cos q}{\sqrt{l^2 + r^2 - 2lr \cos q}} \right. \\ &\quad \left. + \frac{l_{s0} lr \sin^2 q}{\sqrt{l^2 + r^2 - 2lr \cos q}^3} \right) \end{aligned} \tag{4}$$

Threfore, the stiffness k_q can be adjusted by varying the length r as shown in the equation (4). The stiffness k_q is a nonlinear function of the length r. However, if the inside of () of the right-hand side of the equation (4) does not change largely by varying the length r, the stiffness is linearly adjusted by varying the length r. The stiffness k_q is also a nonlinear function of the angle q. The nonlinearity of the stiffness k_q is shown in the section IV by using a concrete example.

D. Advantage of Proposed Structure

The proposed structure has the following advantages.

1) Weight and Size of Linear Spring: The most important advantage is that we can use smaller and more lightweight linear springs in the proposed structure because of the following reason. At first, we consider available elastic energy U_{ava} of the linear spring as

$$U_{ava} = U_{max} - U, \tag{5}$$

where U_{max} is storable elastic energy that the spring can maximally store without plastic deformation. In the case of the linear spring, the maximum length of the linear spring l_{smax} is determined from the storable elastic energy as $l_{smax} = l_{s0} + \sqrt{\frac{2U_{max}}{k_l}}$. As shown in the equation (2), the potential energy of the spring U increases with deformation of the spring $l_s - l_{s0}$. If the available elastic energy U_{ava} is smaller, the spring plastically deforms by smaller additional deformation. Therefore, how to ensure large available elastic energy U_{ava} is important. However, to increase the storable elastic energy U_{max} linearly affects weight and size of the linear spring. On the other hand, the stiffness of the proposed structure is maximum when the length r is longest. In this case, the spring length l_s at the equilibrium angle $q = 0$ is minimum as shown in the equation (1), and the elastic energy of the spring U is minimum as shown in the equation (2). Then, the available elastic energy U_{ava} of the proposed structure is maximum when the stiffness is maximum. In many of other structures, available elastic energy of elastic elements is minimum when stiffness is maximum. For example, in the case of the effective length adjustment [7], available elastic energy decreases with increase of stiffness, because the stiffness is increased by shortening effective length of elastic elements. In some of other structures [8], [9], [10], [11], available elastic energy is also minimum when stiffness is maximum, because the stiffness is increased by increasing loads acting on elastic elements. Therefore, the proposed structure has the advantage that the linear spring can be smaller and more lightweight due to the above structural effect.

We do not need to concern about low stiffness cases, because deformation of the linear spring δl_s by joint rotation δq becomes smaller in the case of the low stiffness. Therefore, even the available elastic energy U_{ava} in the case of low stiffness is also decreased, we don't need to use large springs.

2) Mechanical Simplicity: Another important advantage of the proposed structure is mechanical simplicity. The proposed structure is composed of almost only the ball screw mechanism and the linear spring. The ball screw mechanism can be not so large and requires not so many mechanical parts. Therefore, the proposed structure can be easy to construct, and small.

3) Range of Adjustable Stiffness: As shown in the equation (4), the stiffness of the proposed structure can be adjusted from 0 to the maximum by varying the length r from 0 to the maximum. Therefore, range of the adjustable stiffness of the proposed structure can be large.

If we vary the length r from negative one, we can realize even negative stiffness. This characteristic may be favorable for some applications.

4) Low Backdrivability: Low backdrivability of the ball screw mechanism is favorable in some cases, because to keep constant stiffness consume only small energy of actuators of the stiffness adjustment devices. It is known that ball screw mechanisms can have low backdrivability.

5) Low Friction: When we keep a constant stiffness, the proposed structure has almost no slide portions. Therefore, low friction is also an advantage of the proposed structure.

6) Work Space: The proposed structure requires not so large work space, because the ball screw mechanism and the spring moves in not so large space. This may be an advantage of the proposed structure.

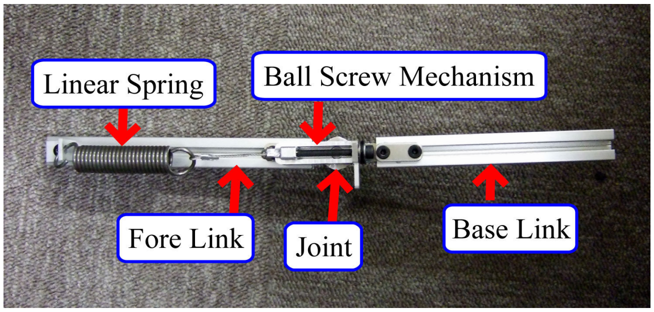

Fig. 3. Developed Hardware

III. DEVELOPED HARDWARE

We developed a hardware as shown in **Fig.3** to verify the effectiveness of the proposed structure.

A. Mechanical Part

The mechanical parts of the developed hardware are shown in **Fig.4**. We adopted aerial aluminum frames as the base link and the fore link. We used a NC machine tool to cut out the base part and nut of the ball screw mechanism, and the bearing holder and shaft holder of the joint from aluminum blocks. The rotating shaft, linear spring, screws, bearings, wire and spring post were commercialized products. The ball screw mechanism was attached to the rotating shaft rigidly. The rotating shaft was attached to the base link rigidly.

B. Size and Weight

The sizes of the mechanical parts were as follows. Height and width of the aluminum frames were 2[cm] respectively, length of the base link was 15[cm], and length of the fore link was 18[cm]. Diameter of the wire of the spring was 2.5[mm], the total number of the coils of the spring was 23, average diameter of the coils was 16[mm], and length of the spring including the hooks was 9[cm]. Height, width and length of the base part of the ball screw mechanism is 14[mm], 15[mm], and 51[mm].

Weights of the mechanical parts were as follows. Weight of the links with the joint was 223[g]. Weight of the spring was 51[g]. Weight of the ball screw mechanism including the nut and the screw was 37[g]. Total weight of the all parts was 311[g].

The developed adjustable stiffness device was smaller and more lightweight than the links with the joint. Therefore, the developed device can be mounted on each joint of multi-joint robots or walking robots like Fig.1.

C. Specification of Spring

The spring can be extended by 52[mm] without plastic deformations. Therefore, we can rotate the joint by more than π[rad] in the case of maximum stiffness. In the cases of lower stiffness, we can also rotate the joint by more than π[rad]. The length from the joint to the one side of the spring l was 19.0[cm]. The stiffness of the linear spring k_l was 4.570[N/mm]. The natural length of the spring l_{s0} was 9[cm]. The spring can passively exert more than 7[Nm] of torque on the joint.

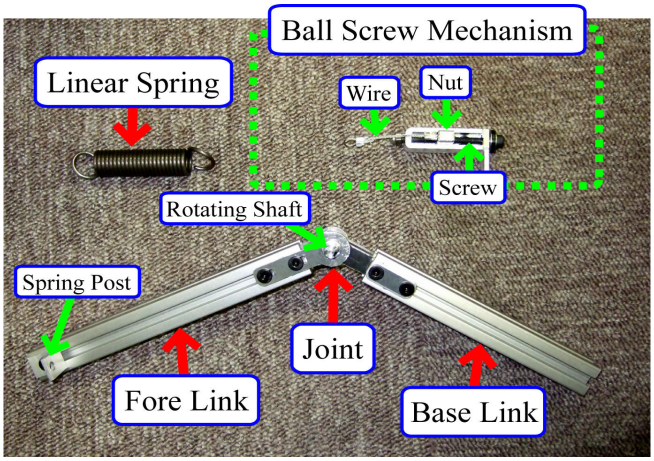

Fig. 4. Mechanical Parts

D. Ball Screw Mechanism

The ball screw mechanism can adjust the position of the nut by rotating the screw. Then, the length r can be adjusted from 34[mm] to 0.0[mm].

We can calculate necessary torque τ_r, which is required to rotate the screw, by using the principle of virtual work.

$$\tau_r \delta q_r = k_l \delta l_s \tag{6}$$

where $q_r \in \Re$ is a rotated angle of the screw. The nut moves 0.8[mm] by rotating the screw 2π[rad]. Then δl_s and δq_r satisfies $\frac{\delta l_s}{\delta q_r} = \frac{0.0008}{2\pi}$. The spring maximally exerts of 234[N] force to the nut. Therefore, to rotate the screw maximally requires 0.030[Nm] of torque theoretically.

E. DC motor for Stiffness Adjustment

We assume that the following DC motor with the gearbox rotates the screw of the ball screw mechanism. The product name of the DC motor is "RE16" developed by Maxon Corporation. Specifications of the DC motor are as follows. Rated power is 4.5[W], rated angular velocity is 1466 [rad/s], rated torque is 0.00442 [Nm], and maximum torque is 0.035[Nm]. The product name of the gearbox is "GP 16 A". Reduction ratio of the gearbox is 29:1.

Then, we can exert 0.13[Nm] of rated torque and 1.0[Nm] of maximum torque to the screw by the DC motor with the

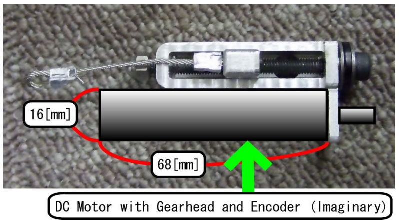

Fig. 5. Ball Screw Mechanism with DC Motor

gearbox. Therefore, the motor with the gearbox can rotate the screw enough.

In the case of the rated angular velocity of the DC motor, the angular velocity of the screw becomes 8 [revolutions/s]. Then, the nut moves with 6.4[mm/s] of velocity. Therefore, to adjust stiffness from the minimum to the maximum requires about 5[s] in the case of the rated angular velocity.

The motor is assumed to have an optical encoder as an angle sensor. Radius of the motor with the gearbox and the encoder is 16[mm], total length of them is 68[mm], and weight of them is 80[g]. Therefore, we can attach the motor with the gearbox to the ball screw mechanism like **Fig.5**. The total weihgt of the adjustable stiffness device including the motor is still 168[g]. This weight seems not unreasonable for the kind of walking/running robots like Fig.1.

F. Adjustment of Equilibrium Angle

Depending on applications, we need to adjust equilibrium angle of the joint. In such cases, we can adjust the equilibrium angle by rotating the ball screw mechanism around the joint. Then, the equilibrium angle is linearly adjusted by the rotated angle of the ball screw mechanism. However, to rotate the ball screw mechanism requires one more actuator.

IV. EXPERIMENT

We conducted an experiment to test the developed hardware.

A. Condition

We measured torque from the developed adjustable stiffness device. Since the proposed structure is symmetric, the torque of one side rotation of the joint is the same as the other side of rotation. Therefore, we measured the torque of only one side of rotation ($q > 0$). The length from the joint to the nut r is adjusted as $r = 34, 23, 17, 11, 8, 4, 0$[mm]. We measured the torque at the angles q from 0[rad] to $\frac{\pi}{2}$[rad] at the $\frac{\pi}{18}$[rad] intervals. To compare the measured torque and the theoretical one, we calculated the equation (4).

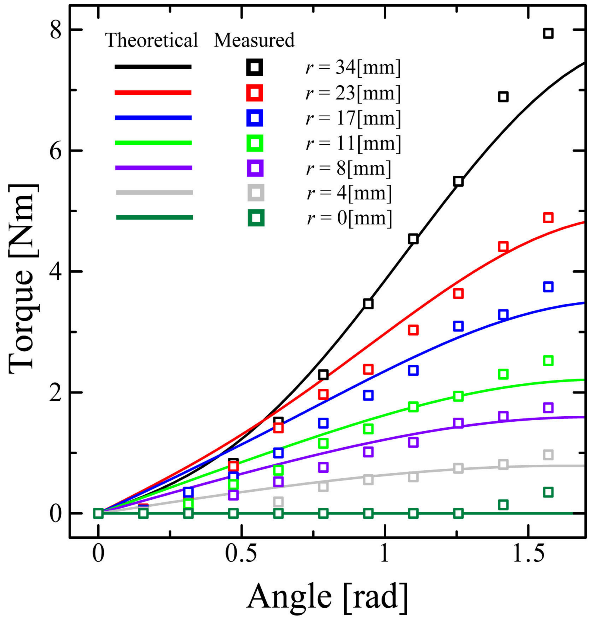

Fig. 6. Experimental Results

We also measured torque, which is maximally required to rotate the screw of the ball screw mechanism, and checked backdrivability of the ball screw mechanism.

B. Result

Experimental results with the theoretical ones are show in **Fig.6**. As show in the Fig.6, the stiffness could be adjusted by varying the position of the nut r. The measured torque roughly agreed with the theoretical one. We may increase accuracy of the agreement by improving the experimental condition, because we measured the torque by hand. Since the stiffness is the nonlinear function of r as shown in the equation (4), some region of the stiffness in the case of $r = 34$[mm] was lower than the other cases. However, the stiffness in the case of $r = 34$[mm] was totally larger than the other cases. The stiffness in the other cases is almost linearly adjusted by varying r. Even though the stiffness is also the nonlinear function of q, the nonlinearity was not so strong in the measured region of the experiment. In the case of $r = 0$, we measured some torque even the theoretical value was 0. The reason seems a physical interference between the wire and the nut.

To rotate the screw of the ball screw mechanism required maximally 0.15[Nm] of torque. Since the theoretical value in the section III-D was 0.030[Nm], the measured torque is much larger than the theoretical one. The reason of the difference seems friction of the ball screw mechanism. Since the spring force produced large torque on the nut of the ball screw mechanism, the friction between the nut and the screw seemed to be greatly increased. Nevertheless, the assumed actuator in the section III-E can maximally exert 1.0[Nm] of torque. Therefore, we can rotate the ball screw mechanism by the assumed actuator in the section III-E.

The nut did not move almost at all by torque from the spring, and the ball screw mechanism had few backdrivability. Therefore, the developed hardware requires no energy consumption to keep constant stiffness.

V. CONCLUSION

This paper proposed a new mechanical structure to develop adjustable stiffness devices with lightweight and small size. The proposed structure is composed of a ball screw mechanism and a linear spring. Then, the proposed structure does not require a lot of mechanical parts. An advantage of the structure is that available elastic energy of the spring is maximum when the stiffness is maximum. Therefore, the spring of the proposed structure can be smaller and more lightweight than many of other structures.

We developed an actual hardware to verify the effectiveness of the proposed structure.

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