Development of a Variable Stiffness Function for a New Multifunctional Wire Driven Joint Mechanism

Katsuaki Suzuki
Life Science and Systems Engineering, Kyushu Institute of Technology
2-4 Hibikino,Wakamatsu-ku, Kitakyushu 808-0196, Fukuoka, Japan
E-mail: suzuki.katsuaki448@mail.kyuteck.jp

Yuya Nishida
Life Science and Systems Engineering, Kyushu Institute of Technology
2-4 Hibikino,Wakamatsu-ku, Kitakyushu 808-0196, Fukuoka, Japan
E-mail: ynishida@lsse.kyutech.ac.jp

Kazuo Ishii
Life Science and Systems Engineering, Kyushu Institute of Technology
2-4 Hibikino,Wakamatsu-ku, Kitakyushu 808-0196, Fukuoka, Japan
E-mail: ishii@brain.kyutech.ac.jp

Abstract

A mechanical variable stiffness can adapt to external forces beyond the control cycle, such as overturning of walking robots, which can help solve problems such as actuator and joint destruction. In this research, we will clarify the structure of a two-input, one-output joint mechanism that can realize three functions: normal motion, instantaneous motion, and variable stiffness function. As part of the development of the variable stiffness function, a mathematical model is derived and simulated for the relationship between the joint angle of the output link and the disturbance torque when a disturbance torque is applied to the output link of the proposed mechanism.

Keywords: Mechanical variable stiffness, Link mechanism

1. Introduction

When robots and humans work together, making the joints of robots flexible is an important issue to prevent robots from harming humans. One way to make robot joints flexible is to achieve variable stiffness. Methods using software, such as impedance control and force control, have been put to practical use in industrial robots as a means of achieving variable stiffness. However, it has some problems such as difficulty in responding to responses exceeding the control cycle. On the other hand, methods to realize variable stiffness mechanically have also been researched [1],[2],[3],[4],[5],[6],[7],[8]. Sonoda et al. proposed a variable-stiffness joint mechanism that mimics living organisms [9]. This mechanism uses two motors, two cams, and wires to achieve variable stiffness and does not use springs. An arbitrary reduction ratio is designed using a cam, and a nonlinear spring element is realized. Since the posture and stiffness can be controlled only by the magnitude of the torque applied to the two motors, the stiffness can be changed at high speed compared to other mechanisms. As a feature of these mechanisms, each mechanism uses two motors, and realizes a variable stiffness function by using an antagonistic structure and a nonlinear spring element. On the other hand, the problem is that it is difficult to use in applications that require rapid motion. The authors have developed a joint mechanism that can perform normal and instantaneous movements in order to expand the range in which the robot can be active [10]. In this paper, as a new function of the joint mechanism that we have developed so far, which is capable of normal motion and rapid motion, we propose a method to realize variable stiffness by devising the driving method of two motors while keeping the existing mechanism. Section 2 describes how the proposed mechanism achieves variable stiffness. In Chapter 3, we derive mathematical formulas and analyze the torque and stiffness with respect to the angle of the output link passively rotated by the disturbance torque. Section 4 presents the conclusions.

2. Variable stiffness function of the proposed mechanism

Fig.1 shows how the proposed mechanism realizes variable stiffness. First, we assume a state in which the initial displacement of the spring is 0, that is, the state in which the two motors are braked with the length of the spring at its natural length. When a disturbance torque T_q is applied to the output link while the brakes are applied to the two motors, tension acts on one of the wires according to the magnitude and direction of the torque, and the slider moves in translation. At this time, slackness occurs in the wire on the side where tension does not occur. At the position where the tension of the wire and the compressive force acting on the spring are balanced, the movement of the slider stops and the passive rotational motion of the output link also stops. This indicates that the output link passively displaced according to the disturbance torque T_q applied to the output link. Here, as shown in Fig.1, we assume a state in which the internal spring is displaced by ε_{sp} and two motors are braked. As in the case where the initial displacement of the spring is 0, applying a disturbance torque to the output link causes tension to act on the wire. The passive motion of the output link then ceases at the point where the tension of the wire and the compression force of the spring are balanced. Comparing the initial displacement of the spring of 0 and ε_{sp}, in the case of ε_{sp}, a compressive force acts on the spring before the load is applied to the output link. Therefore, the passive displacement of the output link does not occur unless the spring contraction direction component of the tension acting on the wire due to the disturbance torque exceeds the spring compression force accumulated by the initial displacement of ε_{sp}. In addition, when the force acting on the spring due to the disturbance torque exceeds the compressive force acting on the spring due to the initial displacement of ε_{sp}, passive displacement of the output link occurs, but compared to the case where the initial displacement is 0, The displacement becomes smaller. In other words, the stiffness of the joint can be changed by adjusting the initial displacement of the spring inside the mechanism. In the proposed mechanism, such a principle is applied to realize a variable stiffness function.

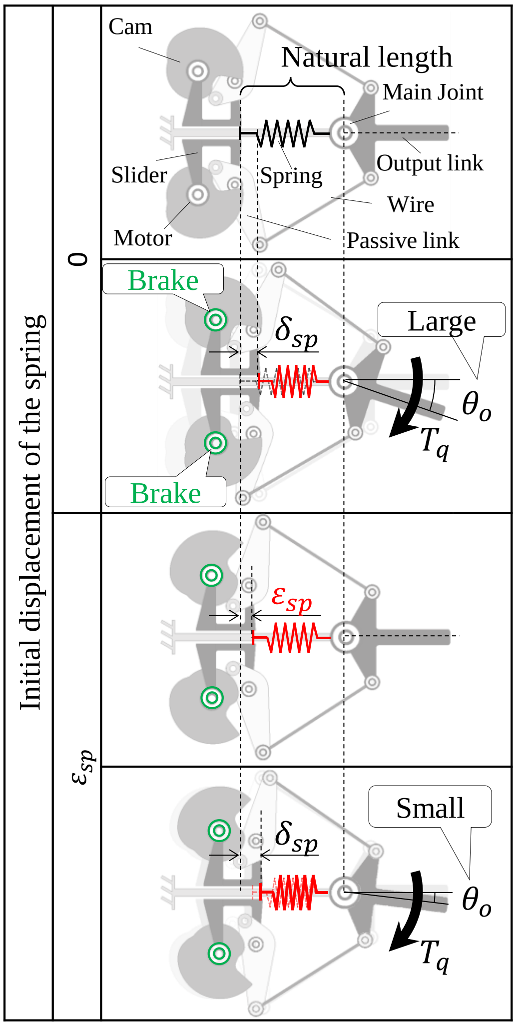

Fig.1 Variable stiffness function of the proposed mechanism

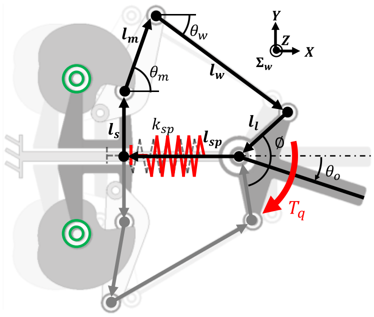

Fig.2 Link vectors of the proposed mechanism

3. Analysis of an output characteristics related to stiffness

In the case of using variable stiffness, we consider the disturbance torque and rotational stiffness of the output link that change with the initial displacement of the spring. Fig.2 shows the link vectors of the proposed mechanism. When a disturbance torque is applied to the output link, the output link rotates. Then, the rotational motion of the output link is converted into the translational motion of the slider through the wire. At this time, the spring inside the mechanism is compressed, and tension acts on the wire due to the compressive force of the spring. Therefore, in order to apply a disturbance torque to rotate the output link, it is necessary to apply a disturbance torque of the same magnitude as the torque generated around the output link due to the internal force such as wire tension. The relationship between the disturbance torque T_q and the internal force acting inside the mechanism is expressed by the following equation from the geometric relationship.

$$T_q = sign(\theta_o) k_{sp} \delta_{sp} l_l (-\sin\beta + \tan\theta_w \cos\beta) \tag{1}$$

The rotational stiffness K of the output link is expressed by the following equation by differentiating the disturbance torque T_q given to the output link by the angle θ_o of the output link.

$$K = \frac{dT_q}{d\theta_o} = k_{sp} l_l \delta_{sp} \left[\frac{l_l \cos^2\beta \,(1 + \tan^2\theta_w)}{l_w \cos\theta_w} - \tan\theta_w \sin\beta - \cos\beta \right] + k_{sp} l_l^2 (\sin\beta - \cos\beta \tan\theta_w)^2 \tag{2}$$

Here, β used in formulas (1) and (2) is expressed by the following formula.

$$\beta = \begin{cases} \theta_o - \frac{\emptyset}{2} \ (\theta_o \geq 0) \\ -\theta_o - \frac{\emptyset}{2} \ (\theta_o < 0) \end{cases} \tag{3}$$

Furthermore, the wire angles θ_w and θ_m are expressed by the following equations from the geometrical relationship.

$$\theta_w = \sin^{-1}\left(\frac{l_s + l_m \sin\theta_m - l_l \sin\beta}{l_w}\right) \tag{4}$$

$$\theta_m = \cos^{-1}\left(\cos\theta_{mi} - \frac{\varepsilon_{sp}}{l_m}\right) \tag{5}$$

Fig.3 shows the profile of the disturbance torque T_q of the output link and the angle θ_o of the output link when the initial displacement ε_{sp} of the spring is changed to 0 mm, 10 mm, and 20 mm using equation (1). Fig.3 shows the profile of the disturbance torque T_q of the output link and the angle θ_o of the output link when the initial displacement ε_{sp} of the spring is changed to 0 mm, 10 mm, and 20 mm using equation (1). Similarly, using equation (2), Fig.4 shows the profile of the rotational stiffness K and θ_o of the output link when ε_{sp} is changed to 0 mm, 10 mm, and 20 mm. This analysis was performed using the parameters shown in Table 1. As a result, it was confirmed that the apparent stiffness can be changed by changing the magnitude of the reaction force according to the initial displacement of the spring.

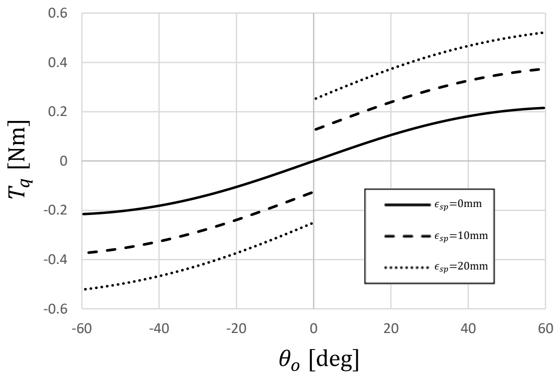

Fig.3 Relationship between rotation angle of output link and disturbance torque

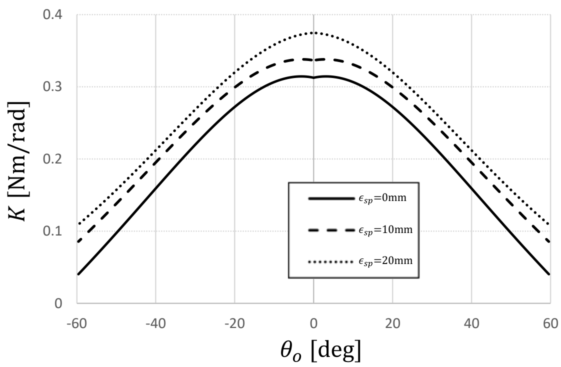

Fig.4 Relationship between output link rotation angle and rotational stiffness

©The 2023 International Conference on Artificial Life and Robotics (ICAROB2023), Feb. 9 to 12, on line, Oita, Japan

Table 1 Parameters for analysis

k_{sp}	Spring constant	500N/m
l_l	Length of $\boldsymbol{l_l}$	0.025m
l_s	Length of $\boldsymbol{l_s}$	0.012m
l_w	Length of $\boldsymbol{l_w}$	0.068m
l_{spn}	Length of $\boldsymbol{l_{spn}}$	0.092m
l_m	Length of $\boldsymbol{l_m}$	0.03m
l_{cp}	Length of $\boldsymbol{l_{cp}}$	0.0181m
$\emptyset$	Direction of $\boldsymbol{l_l}$	180°
θ_{max}	Maximum movement range	+60°
θ_{min}	Minimum movement range	-60°
θ_{mi}	Absolute angle of $\boldsymbol{l_m}$ when θ_o=0,l_{sp}=l_{spn}	126°

4. Conclusion

In this paper, we presented a method for realizing variable stiffness in the proposed mechanism that can perform normal and rapid motions. In addition, the relational expression between the joint angle of the output link and the disturbance torque and the expression for the rotational stiffness were derived. From the analysis results, it was found that the magnitude of the disturbance torque required to rotate the output link changes according to the initial displacement of the spring, and the apparent stiffness changes. Therefore, it was clarified that the proposed mechanism can achieve variable stiffness by adjusting the initial displacement of the spring.

References

1. Masafumi Okada. Human-Like Compliant Motion and Its Mechanism. Journal of Robotics Society of Japan, 1999, 17. 6: 782-785.
2. LAURIN-KOVITZ, Kirsten F.; COLGATE, James Edward; CARNES, Steven DR, Design of components for programmable passive impedance . In: ICRA. 1991. p. 1476-1481.
3. Jin'ichi YAMAGUCHI, et al. Development of a Bipedal Humanoid Having Antagonistic Driven Joints. Society of Biomechanisms Japan, 1998, 14: 261-271.
4. Toshio Morita, et al. Development of Force-Controlled Robot Arm Using Mechanical Impedance Adjuster. Journal of Robotics Society of Japan, 1998, 16. 7: 1001-1006.
5. Toshiro NORITSUGU, tomu WADA. Applications of Artificial Rubber Muscle to Robot Control. Journal of Robotics Society of Japan, 1991, 9. 4: 502-506.
6. Tomoya Inaba, Toshiki Nakazawa, Koichi Koganezawa. Stiffness and Angle Control of Antagonistially Driven Joint using the Actuator with Non-Linear Elastic System (ANLES) T. Journal of Robotics Society of Japan, 2008, 26. 4: 381-388.
7. Kazuhito HYODO, Hiroaki KOBAYASHI. A Study on Tendon Controlled Wrist Mechanism with Nonlinear Spring Tensioner. Journal of Robotics Society of Japan, 1993, 11.8: 1244-1251.
8. SONODA, Takashi, et al, Development of antagonistic wire-driven joint employing kinematic transmission mechanism. *Journal of Automation Mobile Robotics and Intelligent Systems*, 2010, 4: 62-70.
9. SUZUKI, Katsuaki, et al. A new rotary actuator capable of rapid motion using an antagonistic cam mechanism. *Journal of Advances in Artificial Life Robotics*, 2020, 1.3: 143-151.

Authors Introduction

Dr. Katsuaki Suzuki

He received his Ph.D. from the Department of Life Science and Systems Engineering, Graduate School of Life Science and Systems Engineering, Kyushu Institute of Technology, Japan in 2021. His research interests include joint mechanisms and their applications.

Dr. Yuya Nishida

He is an Associate Professor at Graduate School of Life Science and System Engineering, Kyushu Institute of Technology, Japan. His research interests include filed robotics, its application, and data processing.

Prof. Kazuo Ishii

He is a Professor at Graduate School of Life Science and System Engineering, Kyushu Institute of Technology, Japan. His research intetrests include field robots and intelligent robot systems.