Development of a Rotary Actuator Capable of Multidirectional Rapid Motion and Variable Stiffness

Katsuaki Suzuki
Kumamoto Industrial Research Institute, 3-11-38 Higashi machi, Higashi-ku, Kumamoto 862-0901, Japan

Yuya Nishida
Kyushu Institute of Technology, 2-4 Hibikino, Wakamatsu-ku, Kitakyushu 808-0196, Fukuoka, Japan

Kenji Kimura
Department of Control Engineering, National Institute of Technology, Matsue College,
14-4 Nishi-ikuma-cho, Matsue-shi, Shimane, 690-8518, Japan

Kazuo Ishii
Kyushu Institute of Technology, 2-4 Hibikino, Wakamatsu-ku, Kitakyushu 808-0196, Fukuoka, Japan
E-mail: k-suzuki@kumamoto-iri.jp, y-nishida@lsse.kyutech.ac.jp,
k-kimura@matsue-ct.jp, ishii@brain.kyutech.ac.jp

Abstract

With the advancement of automation and digital transformation in the manufacturing industry, it is expected that industrial machines will be required to perform new tasks. Enhancing the multifunctionality of actuators is one approach to achieving these tasks. This paper proposes a new mechanism that combines two types of cams with different contour shapes, springs, two motors, and other mechanical components, and introduces an electric actuator incorporating this mechanism. The key feature of this actuator is its ability to achieve three functions (normal motion, rapid motion, and variable stiffness) while maintaining the same output characteristics, even when the initial posture of the output shaft is changed by switching the driving patterns of the two motors.

Keywords: Rapid motion, Variable stiffness, Cam mechanism

1. Introduction

The driving of output shafts using actuators and reduction gears (normal motion) is used in the driving of various machines, such as robot arm handling operations and gripper grasping operations. One way to increase the number of tasks that can be performed by robot arms and grippers is to improve the functionality of the joints and achieve operations other than normal motions. One such operation is driving the joints at high torque and high speed. To achieve this operation using actuators and reduction gears, a high-output motor is required, which would result in a larger size. Therefore, there is a method that uses the energy stored in the actuator by means of springs or compressed air, etc., and uses this as the driving source to drive the output axis (rapid motion) at a higher output than the actuator used for storage [1], [2]. In addition, one of the important functions for improving the functionality of the joints is the ability to adjust the rigidity. The most common methods for adjusting stiffness are compliance control and force control using force sensors, but these methods have problems such as difficulty in responding to external disturbances that exceed the control cycle. Therefore, there is a method for mechanically adjusting the stiffness of the joint (variable stiffness) using two actuators, a nonlinear spring element, and an antagonistic structure [3], [4].

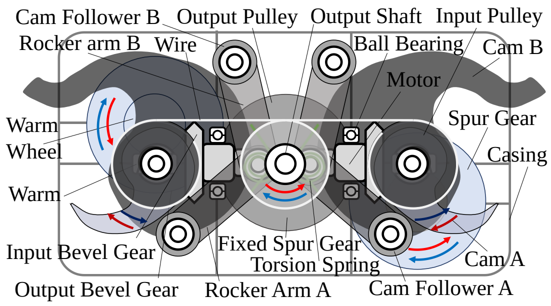
When multiple units of such individual mechanisms and actuators are mounted to expand functionality, the problems of size increase and control system complexity arise. Therefore, we developed a joint mechanism that can realize three functions (normal motion, rapid motion, and variable stiffness) using only two motors by integrating the mechanisms well [5], [6]. As a result of numerical analysis and actual device testing, we clarified that the three functions can be realized. However, when the initial posture of the output part of the developed joint mechanism is changed, it is difficult to realize normal motion, rapid motion, and variable stiffness with the same output. In addition, its range of motion is also limited. Therefore, in this study, we aim to develop a new rotary actuator that can achieve the same output characteristics for the three functions (normal motion, rapid motion, and variable stiffness) even when the output axis posture is changed, by combining two motors and several mechanical elements such as cams and springs. In this paper, we describe the design concept, structure, and drive method of the rotary actuator, and analyze rapid motion and discuss the results.

2. Design Concept and Overview

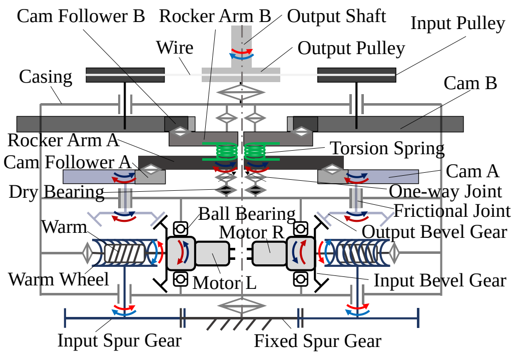
The design concept for the newly developed rotary actuator was set as follows.

- One output axis realizes three functions (normal motion, rapid motion, variable stiffness).
- Even if the output axis posture is changed, the three functions are realized with the same output characteristics.
- The above conditions are realized using two motors and several mechanical elements.

The rotary actuator, which was designed according to the design concept, is shown in Fig. 1. In order to realize the design concept, this actuator incorporates nine key ideas. The first is a system that switches the driving pattern of the two motors. This system is also used in the joint mechanisms we have developed so far, and it is possible to realize multiple functions by combining the rotational directions of the two motors [5], [6]. The second is a structure in which the output shaft, casing, and the rotation axis of the fixed spur gear are arranged on the same axis. With this structure, if the casing is rotated with respect to the fixed gear, the output shaft can also rotate at the same angular velocity as the casing. Furthermore, the drive shaft can also be rotated with respect to the casing. The third is a cam mechanism developed by Sonoda et al. that achieves variable stiffness [4]. Due to the antagonistic structure and the increase in the radius of the cam, the reduction ratio decreases, so it is possible to output an anti-torque against external disturbances acting on the output shaft. Fourth, there is a cam mechanism developed by Amil et al. that achieves energy-saving compression and release of the spring [2]. Due to the increase in the radius of the cam, the reduction ratio increases, so it is possible to compress the spring with energy savings. In addition, a notch is provided in the cam follower that allows it to drop suddenly, enabling the release of the spring. The fifth is a cam mechanism that achieves a self-locking function. This mechanism intentionally sets the pressure angle for cam mechanism A. Furthermore, a one-way joint and a dry bearing are incorporated into the rotating joint of rocker arm A. The vertical resistance force generated by the pressure angle and the friction coefficient of the dry bearing can generate a large frictional force in one direction of rotation. Therefore, when an external disturbance acts on the output shaft, it is possible to prevent back driving of Cam A. The sixth feature is a structure in which two cams perform work on a single spring that is incorporated between the two cam mechanisms. By sharing a single spring between two cam mechanisms with different purposes, it is possible to achieve a cam mechanism with no trade-offs in each mode. The seventh feature is a structure that switches between motor shaft drive and casing drive. This structure enables the motor shaft drive and cam drive to be separated. The eighth is the self-locking function of the worm gear. And the ninth is the structure that the casing does not rotate unless two spur gears rotate in the same direction at the same time. These two ideas prevent the casing back drive against the fixed gear when a disturbance acts on the output shaft or when the motor is driven on only one side. And the output shaft can be back-driven against the casing. By optimally



(a) Top view



(b) Front view

Fig.1 Rotary actuator

Table 1 Drive Pattern

Motor L	Motor R	Torsion Spring	Output Shaft	State
Forward	Forward	Natular position	Forward	Normal motion Low Stiffness
Reverse	Reverse		Reverse	
Forward	Forward	Compressed	Forward	Normal motion High Stiffness
Reverse	Reverse		Reverse	
Reverse	Forward	Compression	Stop	Compression Adjustment
Forward	Reverse	Extension		
Reverse	Stop	Rapid Extension	Forward	Rapid motion Spring release
Stop	Forward		Reverse	
Stop	Stop	Natular position	Forward	Disturbance acts Low Stiffness
			Reverse	
Stop	Stop	Compressed	Forward	Disturbance acts Low Stiffness
			Reverse	

combining these nine technologies, we have achieved an actuator that satisfies the design concept.

Table 1 shows the correspondence between drive patterns and functions. When the output shaft is operated normally, Motors L and R rotate in the same direction. This causes the casing body to rotate, and the output shaft to rotate. To adjust the spring force, rotate Motors L and R in opposite directions. In this casing, the two cams A rotate via the bevel gear. The combination of the rotation direction of the two motors achieves compression and extension of the spring, and the output shaft rigidity can be adjusted. To move the output shaft in the forward direction momentarily, first rotate motors L and R in the opposite direction to move cam follower A to the vicinity of cam A's maximum radius. Next, if you reverse the rotation of Motor L only, the cam follower will fall out of the notch, and the output shaft will rotate via Cam Mechanism B due to the force of the torsion spring. If you reverse the rotation direction of Motor L and Motor R, you can drive in the reverse direction. If the two motors are stopped and an external torque acts on the output shaft, the output shaft will back-drive against the casing. In this way, because the position of the casing itself changes during normal motion, it is possible to achieve three functions with the same output characteristics for various angles.

3. Analysis of rapid motion

Using cam B, which is designed for variable stiffness, we will check the output characteristics when performing rapid motions in the analysis. The model of the cam mechanism B used in the analysis is shown in Fig. 2. In this model, we assume that the pressure angle when the cam and cam follower come into contact is always 90 degrees. By setting the pressure angle to 90 degrees, the force acting in the horizontal direction to the rocker arm can be canceled, so the loss due to rolling friction, etc. can be reduced[2]. In addition, when the angle of the rocker arm θ_r is 0 degrees, the distance between the cam follower and the cam's rotational joint becomes l_{cmin}, and d in Fig. 2 becomes 0. Also, because the pressure angle is always 90 degrees, as θ_r increases, d increases nonlinearly and rapidly.

When the radii of the input pulley and output pulley, which are on the same axis as cam B, are the same, the torque acting on the output shaft, cam B, and rocker arm can be expressed by the following formula using the distance d and rocker arm length l_r, based on geometric relationships.

$$T_o = T_c = \frac{d}{l_r} T_r \tag{1}$$

Therefore, the reduction ratio between the output link and the rocker arm B is expressed by the following formula.

The value of d changes as the angle of rotation of the

$$G = \frac{d}{l_r} \tag{2}$$

rocker arm changes. If G is expressed as a variable θ_r and various constants, it can be expressed by the following formula due to geometric relationships.

$$G = 1 - cos\theta_r + \frac{l_{cmin}}{l_r} sin\theta_r \tag{3}$$

The torque accumulated in a torsion spring is expressed by the following formula from Hooke's law, based on the spring constant and angular displacement of the torsion spring.

$$T_r = k_{sp} \delta\theta_r \tag{4}$$

Therefore, the torque acting on the cam during a quick movement can be expressed by the following formula.

$$T_o = k_{sp}(1 - cos\theta_r + \frac{l_{cmin}}{l_r} sin\theta_r)\delta\theta_r \tag{5}$$

The reduction ratio G and output torque T_o analyzed using Eq. (3) and Eq. (5) are shown in Fig. 3, and the design parameters used in the analysis are shown in Table 2. Rocker arm B is defined as being able to rotate from to . The initial posture of rocker arm B at the start of rapid motion is $ini(\theta_r)$. The displacement of the spring charged by Cam A is $max(\delta\theta_r)$. If you check the reduction ratio in Fig. 3, you will see that the reduction ratio is always less than 1. Also, the reduction ratio decreases rapidly as the output shaft rotates. This is because the moment arm decreases as the cam rotates. The torque characteristics show a rapid decrease in the initial stages of operation. This is because the stored spring force decreases and the reduction ratio increases rapidly. It has been theoretically proven that when rapid motion is performed using a cam designed for variable stiffness, the output characteristics will be more focused on speed than torque.

Table 2. Design parameters

k_{sp}	Spring constant	10Nm/rad
Rf	Radius of Cam follower	0.005m
R_{cmin}	Minimum radius of Cam A	0.01 m
l_r	Length Rocker arm A	0.05 m
$max(\theta_r)$	Maximum movement range	+45°
$min(\theta_r)$	Minimum movement range	+5°
$ini(\theta_r)$	Initial Position	+22.5°
$max(\delta\theta_r)$	Maximum Angular Displacement	17.5°

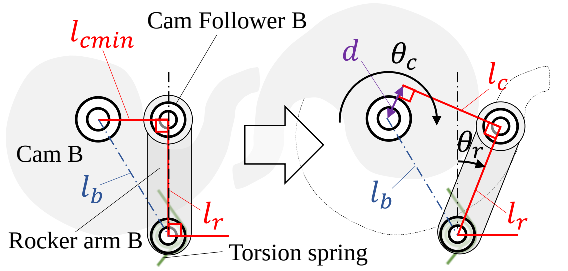


Fig. 2 Cam B model

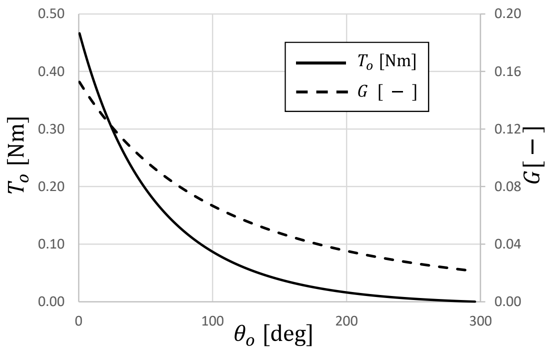


Fig. 3 Output torque and reduction ratio during rapid

4. Conclusion

In this paper, we have presented a new actuator design concept, structure, and method for realizing each function. The proposed mechanism has the potential to realize three functions in various directions while maintaining similar output characteristics. In addition, we analyzed the output characteristics when rapid motion is performed using a cam designed for variable stiffness. The reduction ratio decreases rapidly as the output shaft rotates, making it effective for applications that emphasize speed. In the future, we will analyze variable stiffness and conduct actual machine tests to evaluate the feasibility of each function.

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Authors Introduction

Dr. Katsuaki Suzuki

He is a Researcher at the Kumamoto Industrial Research Institute, Japan. He received his Ph.D. degree from the Kyushu Institute of Technology in 2021. His research interests include joint mechanisms and their applications.

Dr. Yuya Nishida

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

Dr. Kenji Kimura

He is a Lecturer at the Department of Control Engineering, National Institute of Technology, Matsue College, and a Visiting Associate Professor at Chuo University. He received his ME (mathematics) from Kyushu University in 2002 and his PhD (engineering) from the Kyushu Institute of Technology in 2020. His research interests are spherical mobile robots.

Prof. Kazuo Ishii

He received his Ph.D. degrees from Tokyo University, Japan, in 1996. In 2011, he joined Kyushu Institute of Technology, where he is currently a Professor of the Department of Human Intelligence Systems.
His research interests include Underwater Robot, Neural Network and Neural Network.