Development of Antagonistic High Power Joint Mechanism with Cams

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Abstract

Acquiring flexible and agile behaviors as seen in biological systems, the robot can achieve acrobatic movements such as jumping and throwing. These acrobatic movements are expected to extend the range of robot activity. In this research, we propose a special mechanism using a pair of motors, springs and cams, which has three functions: normal operation, instantaneous operation and variable rigidity. Then, we derived a mathematical model of the mechanism and discussed the input-output characteristics of the mechanism by changing the design parameters, and analyzed the difference between the theoretical and measured results.

Keywords: high power joint mechanism, Link mechanism, Cam mechanism

1. Introduction

In order to perform high-speed operations such as jumping and throwing, an actuator that can realize two characteristics, strong force and high speed, is required. As a means to realize instantaneous operation, a mechanism that stores energy in a relatively lightweight mechanical element such as a spring and releases it to extract instantaneous force is often studied. Yamada has developed a closed-loop flexible catapult using jump buckling, and has realized a robot capable of jumping and swimming [1]. Although instantaneous force is generated by jump buckling, the output value is constant, and it is difficult to realize normal operation with low speed and high torque. To create an actuator that can generate instantaneous forces, the authors have developed a high-power joint mechanism that mimics the hind limb of locusts [2]. The developed mechanism can realize not only instantaneous operation but also normal operation that can be applied to walking etc. However, instantaneous operation is possible, but viscous friction loss related to the actuator reducer is large due to the structure of the mechanism. In this study, we propose a mechanism that uses a cam to eliminate this viscous loss and further enhance the function of the mechanism. In the next chapter, we describe the newly developed high-power joint mechanism.

2. Overview of the proposed mechanism

Fig.1 shows the proposed mechanism. The mechanism consists of a pair of motors, cams, cam follower, wire, spring, a slider, a linear guide, and an output link. The feature of the mechanism is that it has three functions: normal operation, instantaneous operation, and change in joint stiffness. In normal motion, the output link moves at the same output as the mounted motor. By rotating two cams on the same axis as the motor in the same direction, the output link moves. In the rapid motion, the output link can instantaneously exhibit more output than the mounted motor. By rotating the two cams in different directions, the spring can be charged with energy. Then, after the cam position reaches the release point, the cam follower disengages from the cam, releasing the stored energy with theoretically no loss. A Cam Charger developed by the authors is applied to this release mechanism[3]. After release, the slider translates using the force stored in the spring as the thrust. The translation of the slider is translated into rotational movement of the output link through the wire. This allows for agile rotational movement. For variable stiffness, it is possible to change the stiffness of the output link main joint. The authors have developed a variable stiffness joint mechanism that utilizes the characteristics of the cam's reduction ratio[4]. The proposed mechanism has a structure in which the rigidity of the joint changes according to the amount of displacement of the spring. This is possible by using two cams to compress the spring into place and keep the cam angle constant.

3. Torque and angular velocity of the output link

From the geometric model, derive an expression for the output value of the mechanism. First, from a static viewpoint, consider the torque generated in the output link. Fig. 1 (d) shows the link vector of the proposed mechanism during rapid motion. The spring force $\boldsymbol{F_{sp}}$ generated in the slider is determined by the spring change amount $\boldsymbol{\delta_{sp}}$ and the spring constant k_{sp}, and is expressed by the following equation.

$$\boldsymbol{\delta_{sp}} = \boldsymbol{l_{sp\_max}} - \boldsymbol{l_{sp}} \quad (1)$$

$$\boldsymbol{F_{sp}} = k_{sp}\boldsymbol{\delta_{sp}} \quad (2)$$

The force F_w generated on the wire is expressed by the following equation, when the angle of the wire is defined as θ_w.

$$F_w = \frac{|\boldsymbol{F_{sp}}|}{cos\theta_w} \quad (3)$$

By using the Jacobi matrix $\boldsymbol{J_{sp}} = (\boldsymbol{l_{l1}} \times \boldsymbol{e_z})$ derived by the cross product of the force $\boldsymbol{F_w}$ and the rotation direction vector $\boldsymbol{e_z}$, the torque T_o generated in the output link is expressed by the following equation.

$$T_o = \boldsymbol{J_{sp}^T F_w} \quad (4)$$

The reduction ratio, which is the input - output relationship when converting the spring force $\boldsymbol{F_{sp}}$ to the output link torque T_o, is expressed by the following equation.

$$G = \frac{T_o}{|\boldsymbol{F_{sp}}|} \quad (5)$$

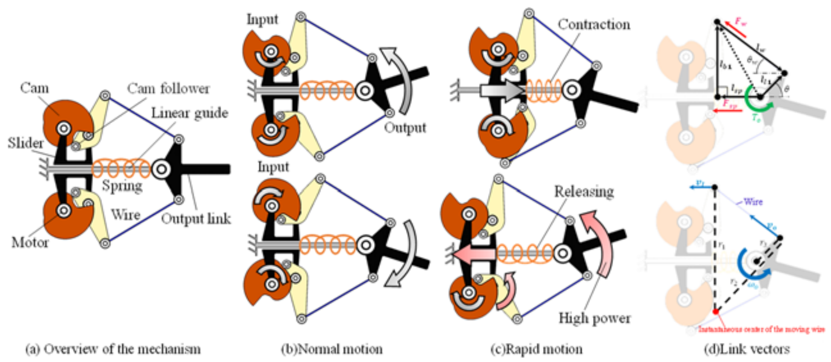

Fig.1 Cam competitive mechanism

In rapid motion,the moving mechanical elements are a slider, two wires, and an output link. Among the moving mechanical elements, the mass and inertia of the slider and output link are so large that they cannot be ignored. Therefore, it is necessary to consider the loss of kinetic energy and derive the velocity that occurs on the output link. If the mass of the slider is m_l, the velocity is v_l, the inertia of the output link is I_o, the angular velocity is ω_o, and the energy completely stored in the spring is E, the instantaneous energy change during operation is as follows.

$$\frac{1}{2}m_l{v_l}^2 + \frac{1}{2}I_o{\omega_o}^2 = E - \frac{1}{2}k_{sp}|\boldsymbol{\delta_{sp}}|^2 \tag{6}$$

Considering the instant center of rotation of wire, it is possible to define the position vectorsl_1, l_2, l_3 shown in Fig. 1 (d), and the relationship between the angular velocity ω_o of the output link and the velocity v_l of the slider is Expression.

$$v_l = \frac{r_1 r_3}{r_2}\omega_o \tag{7}$$

From (6) and (7), the angular velocity of the output link can be expressed by the following equation.

$$\omega_o = \sqrt{\frac{2E - kx^2}{m_l\left(\frac{r_1 r_3}{r_2}\right)^2 + I_o}} \tag{8}$$

4. Analysis of output characteristics

We analyzed how the output characteristics of the mechanism change when the design parameters of the mechanism change. The output characteristics were analyzed using equations (1) and (2). Fig.2 shows the design parameters changed during the analysis and the range of the numerical values. As a result of analysis, several reduction ratios and output torques were classified into seven patterns. For Pattern 1, the reduction ratio is the largest at startup, and gradually decreases with the displacement of the output link. This property is useful when the proposed mechanism is applied to arm joints for throwing. This is because when throwing, the most torque is required during acceleration. Patterns 4, 5, and 6 have a characteristic that the reduction ratio gradually increases, so that continuous torque can be output. These properties can be useful for instantaneous movements in various underwater environments. Fluid resistance may be dominated by inertial force depending on the shape of the output rigid body. In this case, since the fluid resistance approaches a magnitude proportional to the square of the speed, the output unit needs torque even outside the acceleration range.

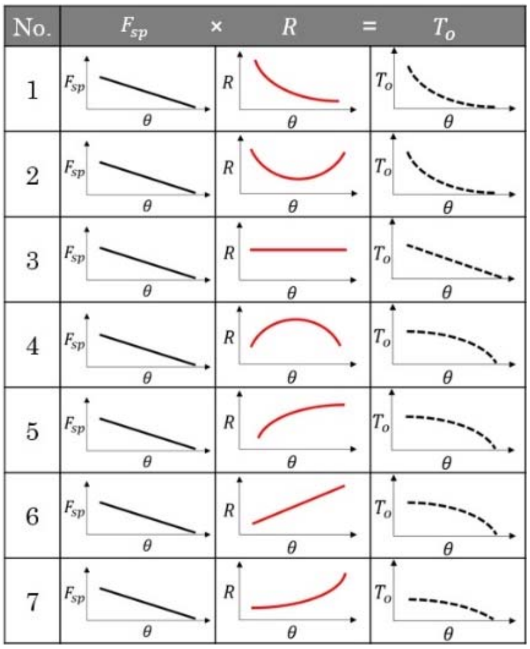

Fig.2 Pattern of the reduction ratio

5. Experimental device

An experimental device was fabricated to evaluate the proposed mechanism on a real machine. Fig. 3 shows the external view of the experimental device, Fig. 4 shows the link vector defined, and Table 1 shows the specifications of the device. k_{sp} can be changed by changing the number of mounted springs.

Table1. Spec of the device

Symbol	Value	Unit
$\boldsymbol{l_{l1}}$	59.55	[mm]
$\boldsymbol{l_{w1}}$	215	[mm]
$\boldsymbol{l_{a1}}$	80	[mm]
$\boldsymbol{l_{b1}}$	107.6	[mm]
$\boldsymbol{l_{c1}}$	28.5	[mm]
$\boldsymbol{l_{d1}}$	11.96	[mm]
$\boldsymbol{l_{sp\_min}}$	164.45	[mm]
$\boldsymbol{l_{sp\_max}}$	211.09	[mm]
$\boldsymbol{\delta_{sp}}$	46.64	[mm]
∅	57.11	[deg]
θ_{max}	+23	[deg]
θ_{min}	-23	[deg]
K_{sp}	1.905 or 3.81	[N/mm]
m_l	1.026	[kg]
I_o	0.00598	[kgm^2]

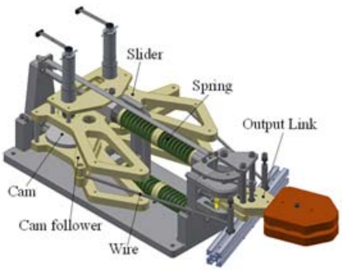

Fig.3 Experimental device

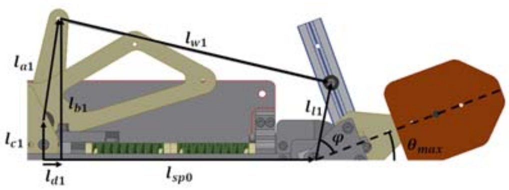

Fig.4 Link vectors of device

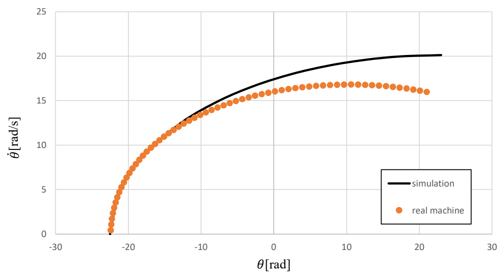

Fig.5 Angular velocity of the output link ($k_{sp} = 1.905$)

6. Performance evaluation test

In order to compare the simulation and the real machine of the angular velocity, the performance was evaluated using an experimental device. The actually measured angular velocity was calculated based on a photographed image of the operation of the output unit in the experimental apparatus taken from above. In the case of $k_{sp} = 1.905$, it can be confirmed from Fig. 5 that the angular velocity between the theoretical value and the measured value is almost the same when θ is around -25 [deg] to 0 [deg]. When θ is 0 [deg] to 25 [deg], the value of the real machine is slightly smaller than the value of the simulation. This factor is considered to be a loss due to viscous friction in the actuator, which is not reflected in the simulation.

In the case of $k_{sp} = 3.81$, from Fig. 6, it can be confirmed that when θ is 0 [deg] to 25 [deg], value of the simulation is greatly reduced with respect to the real machine. This is considered to be because the increase in the speed of the mechanism increased the viscous friction resistance as compared with the case of k_sp=1.905.

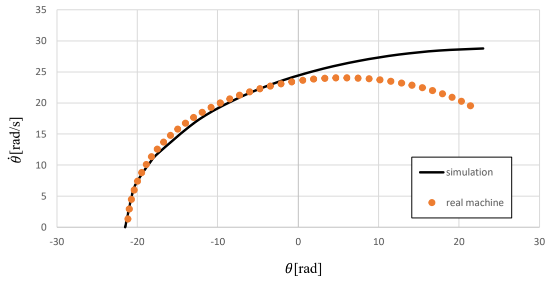

Fig.6 Angular velocity of the output link ($k_{sp} = 3.81$)

7. Conclusion

In this study, we proposed a special mechanism with three functions and discussed the mechanisms to realize these three functions. Next, we constructed a mathematical model for torque and angular velocity during instantaneous operation, and showed that the mechanism can realize some output characteristics by changing design parameters. In addition, we fabricated an experimental device for the mechanism and compared theoretical and measured values of angular velocity during instantaneous operation. The error between the theoretical and measured values was small, confirming the validity of the mathematical model and the actual machine.

As future work, we will discuss normal operation and the function to change the rigidity of the output link. Furthermore, we plan to develop a high-performance hand as one of the applications in the mechanism.

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