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Design of a Variable Stiffness Series Mechanism

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***Abstract* – The elastic joint actuator with outstanding performance in safety, environmental adaptability and energy utilization, has a good application prospect. This paper presents a design of variable stiffness series elastic mechanism based on nonlinear stretching of a linear spring, by adjusting the initial position of the roller on the curved surface, the average output stiffness of the structure is changed. Variable stiffness characteristics are added while retaining the advantage of SEA's ability to calculate output torque. The principle and mechanical realization of variable stiffness structure are presented firstly, and then the design principle of curved surface is given, and SolidWorks simulation data are provided. Finally, a simple joint prototype is built without changing the structure of any core module.**

Index Terms - Variable stiffness actuator (VSA), series elastic actuator (SEA).

I. Introduction

Robots are gradually integrated into human life, and the demand for human-computer interaction is growing. More and more people-centered robots, such as exoskeleton robots, prosthetics, service robots or cooperative robots [1]-[5], will be applied. Therefore, the safety problems brought by human-computer interaction are becoming more and more prominent. The traditional robot joint structure is generally rigid structure, which only considers the position, path, speed, acceleration and other requirements of the actuator, but does not require the stiffness of the control mechanism, which leads to great security risks when the mechanical structure interacts with people, and it is easy to cause great harm to people due to improper operation.

In the field of traditional industry, robots work in a structured environment, and the robot can move repeatedly after programming. In order to meet the production requirements, robots often require high position accuracy, and can accurately track the motion trajectory [1]. However, with the continuous expansion of robot applications, robots have entered other non-industrial fields, such as services, medical care, entertainment, etc. In many cases, the traditional robot is not fully competent for the work, especially the robot when the working position needs to be changed or the environment

is unknown, the robot can't be designed in advance work flow. Under these special requirements, light-weight manipulator emerges as the times require, light-weight manipulator is often required. It has compact structure, good flexibility, high load and deadweight ratio and good environment interaction ability [2]. Variable stiffness joint is generally composed of motor, reducer, variable stiffness components or mechanisms, various sensors and controllers. The variable stiffness joint is relative to the rigid joint, which can be regarded as a driving device, which can track the predetermined trajectory accurately. After reaching the specified position, the output position of the joint will not change within the bearing range, that is, using a large force. The variable stiffness joint can be allowed to deviate from the equilibrium position by a certain angle or distance according to the size of the external force, and the equilibrium position refers to the position where the force or moment generated by the joint is zero [3].

The driver with constant stiffness refers to the introduction of elastic elements into the fully rigid driver. The overall stiffness of the driver is determined by the stiffness of the elastic elements, and the stiffness of the elastic elements is constant, resulting in the constant stiffness of the driver, which is generally driven by a single motor. Series elastic actuator (SEA) [4] is a typical flexible drive with constant stiffness.

G. metta and others of Italian Institute of Technology have designed a compact variable stiffness structure based on SEA. The joint [5] is applied to their "iCub [6]" robot (A humanoid robot the size of a child with 53 degrees of freedom). Lagoda C. et al. designed a robot joint eSEAJ (electric series elastic activated joint) [7] for gait rehabilitation training. Stienen A.H.A and others have developed an exoskeleton robot joint rHEA (rotational hydro elastic actuator) [8]. Wolf s et al. of designed a variable stiffness joint [9,10]. The output stiffness of the joint is only related to VSM. By changing the surface shape of the cam, the joints with different stiffness characteristics can be obtained.

This project adopts the principle of DLR-FSJ [7], and adopts the form of series connection. It is driven by two motors. One large motor (joint motor) adjusts the output position of the joint, and the other small motor (stiffness adjusting motor) adjusts the stiffness of the joint.

II. VARIABLE STIFFNESS MECHANISM

A. Working principle

Fig. 1(a) – (d) shows the principle of the variable stiffness of the structure, the torque is generated by a rotating cam roller and spring system, which transforms the circumferential deformation of the joint into the axial compression deformation of the linear spring, and produces the circumferential torque around the rotating axis, thus changing the stiffness. Different cam disc shapes can be selected to obtain different torque and displacement characteristics. The cam system adds two single torques to get the output torque, which increases the range of torque and stiffness. Two cam discs in the new mechanism are connected by a floating spring. Floating spring refers to that when the cam disc rotates, it will only cause the axial deformation of the spring and will not occur circumferential deformation, which improves the energy utilization to some extent. the elements in the diagram and their relationships are as follows: Two curved surfaces are symmetrical, which are connected by extension spring. A pair of rollers fixed with each other supports the surfaces. The horizontal distance between the two curved surfaces can be changed by a pair of worm gear. Surfaces are constrained by the spring in the vertical direction. When the rollers move along the curved surface, as shown in Fig. 1(a) and (b), surfaces start to move away from each other vertically, the spring's deformation only exists in the vertical direction, which means it doesn't have any circumferential deformation. The tension spring tends to balance at minimum tension when are not under external force.

Fig. 1(c) (d) are same as Fig. 1(a) and (b) except for relative distance D_1. Roller group in Fig. 1(a) and (c) are both in the center of surface while they have different relative positions. The same length of displacement d is performed, then the spring deformation of Fig. 1(b) and (d) changed by Δx_1 and Δx_2, respectively. Obviously, these two values are not equal, which turns out that changes in the horizontal distance of the surface affect the stiffness characteristic.

B. Structure Implementation

Fig. 2(a) shows the 3D model of the roller group and surfaces, and Fig. 2(b) is the assembly method of roller group and surfaces. By coating the structure on the 2D plane in Fig.1 on the cylinder, the surface is generated by scanning excision in mechanical drawing software. The tension spring and the upper surface are installed by angular contact bearing, while the lower surface disc is buckled to the spring directly. Thus, when the surface has horizontal relative displacement in Fig. 1, the two surface disks rotate relatively to each other, and the spring will not have circumferential deformation.

When the robot works normally, due to the change of posture, the external load changes constantly, so the joint is expected to have as large a stiffness range as possible to meet different stiffness requirements. When the load changes, the

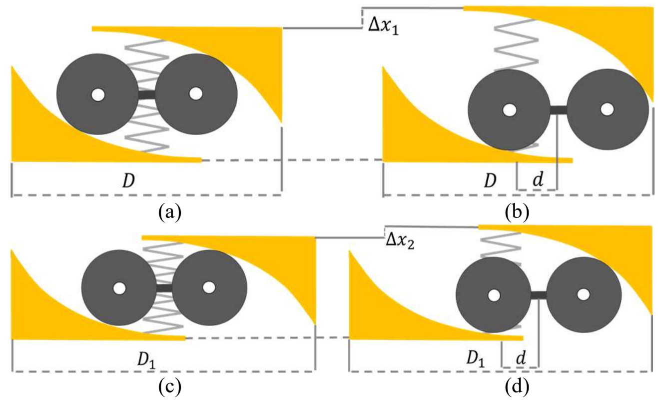


Fig. 1 Design principle. (a) (c) Balance state of roller group and surfaces. (b) (d) The roller groups move the same distance d from (a) and (c) respectively.

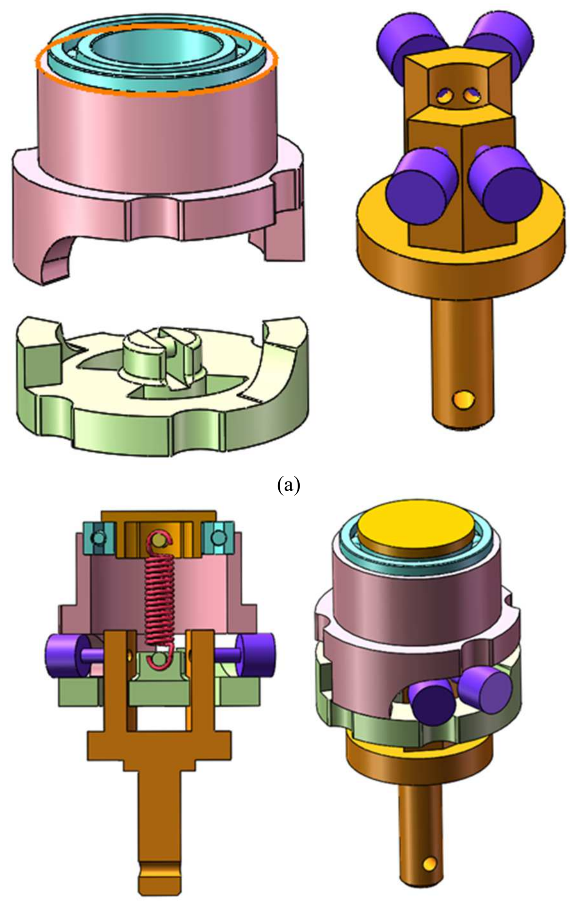
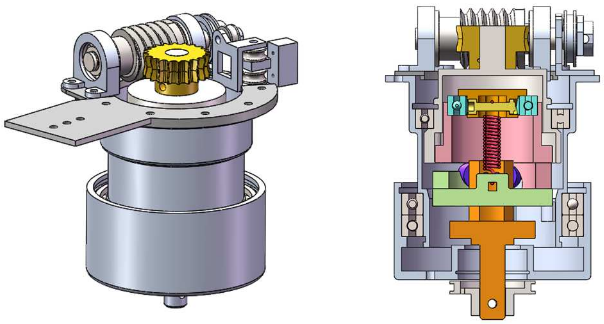


Fig. 2 Structure Implementation. (a) Roller group and surfaces.
(b) The assembly method of roller group and surfaces.

joint is expected to maintain constant stiffness, so as to reduce the operation task and simplify the control. Elastic potential energy can absorb impact kinetic energy and can be used to grasp heavy objects. When the elastic potential energy is too large, it may cause large acceleration and bring some harm; Too small, not conducive to the utilization of energy. There are three kinds of torque displacement characteristic curves of joints: reciprocal, exponential and quadratic. The reciprocal constant stiffness is small, and the quadratic constant stiffness is too



(a) (b)

Fig. 3 Mechanical design. (a) Cross-sectional view of the mechanism. (b) overall 3D model of the structure.

TABLE I
SPECIFICATIONS OF MOTOR

Nominal speed	8040*rpm*
Nominal torque	60.7*m*N•*m*
Nominal current	2.66A
Nominal voltage	24V

TABLE II
SPECIFICATIONS OF GEAR

Reduction	285:1
Mass inertia	15g•cm^2
Max. efficiency	64%
Absolute reduction	15379/54

large. By analogy, the exponential type is more moderate and more universal. Therefore, the torque displacement characteristic curve is set to be exponential in this paper.

C. Mechanical Design

Fig. 3 shows the overall 3D model of the structure. Though it increases the moment of inertia of the link end, the series connection can make the structure more compact, the highly integrated design makes the moment of inertia of the link end still very small compared with that of the whole manipulator.

A pair of worm gear is used to lock and actuate the upper and lower surfaces. The modulus of the worm wheel is 1.5, the index circle diameter is 30*mm*. The index circle diameter of the worm is 25*mm*. In order to obtain the self-locking function, the number of heads is selected as 1. The material of the worm wheel is brass, and the material of the worm is 45# steel. The driving torque into the structure directly drives the shaft of roller group, the main shaft is prepared to be driven with pulley, and the worm gear is driven by a pair of a wire rope. The main drive motor is a 60*watt* brushless motor, which model is maxon EC-max 30. Gearbox model is Planetary Gearhead GP-42-C. The prototype is built preliminarily. The Specifications are shown in TABLE I and II.

After deceleration, the rated speed of the output shaft of the reducer is around 28 *rpm*, and the rated torque is about 11N•*m*, which is enough for the drive of variable stiffness series structure.

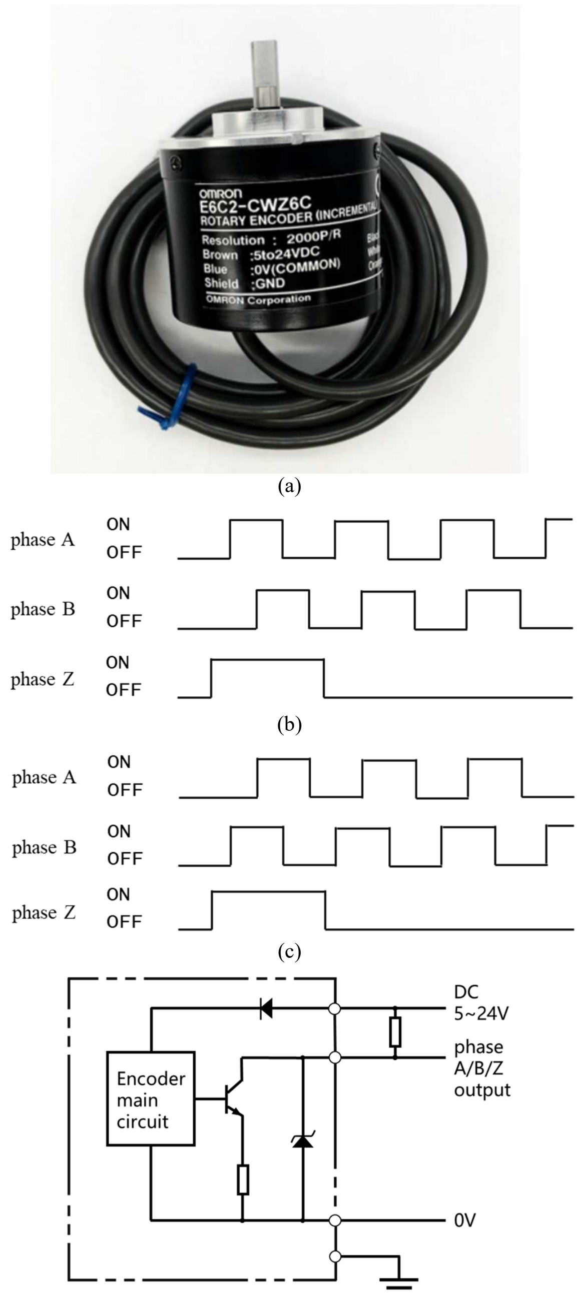
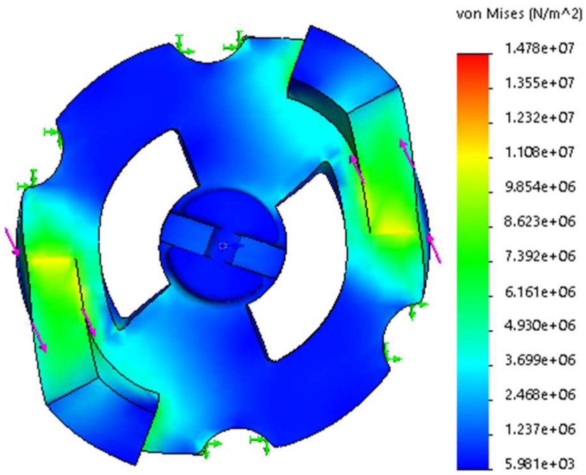
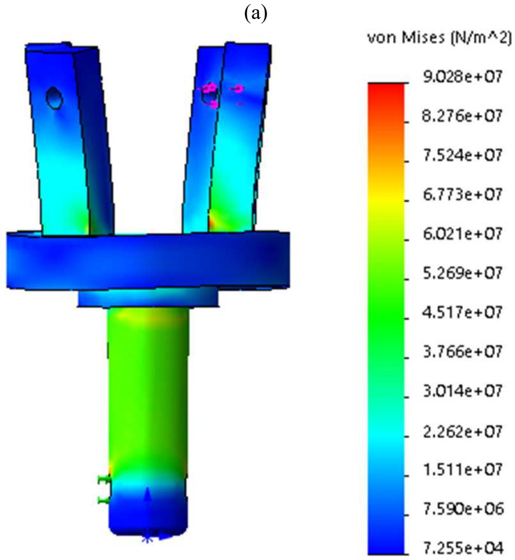


Fig. 4 (a) Incremental encoder. (b) Clockwise output switch logic diagram. (c) Counter clockwise output switch logic diagram. (d) Circuit of encoder and connection.

In order to control the position, force and stiffness of the joint, a measurement system must be designed. The force control can be determined by the compression amount of the spring. In fact, as long as the positions between the upper and lower cam discs and the middle disc need to be accurately measured, the force and stiffness control can be achieved. Omron E6B2-CWZ6C incremental encoder is selected to measure the output shaft angle and velocity, since the output is through an open collector of NPN transistor, it must be connected to a pull-up resistor to produce electrical pulses, as it shown in Fig. 4(d). The specification for that encoder is 2000P/*r*



(a)



(b)

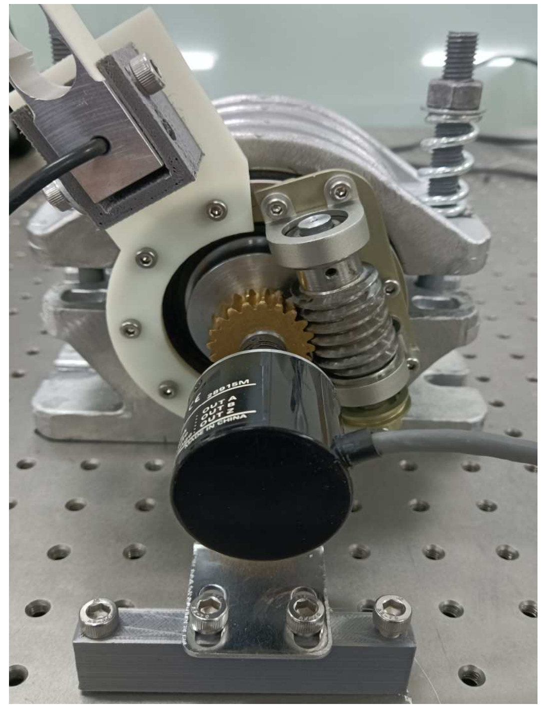
Fig. 5 (a) stress analysis of lower surface. (b) stress analysis of roller seat.

(pulse per rotation), which means that when the output shaft of encoder rotates for 1 cycle, the switching state of phase A and phase B changes 2000 times.

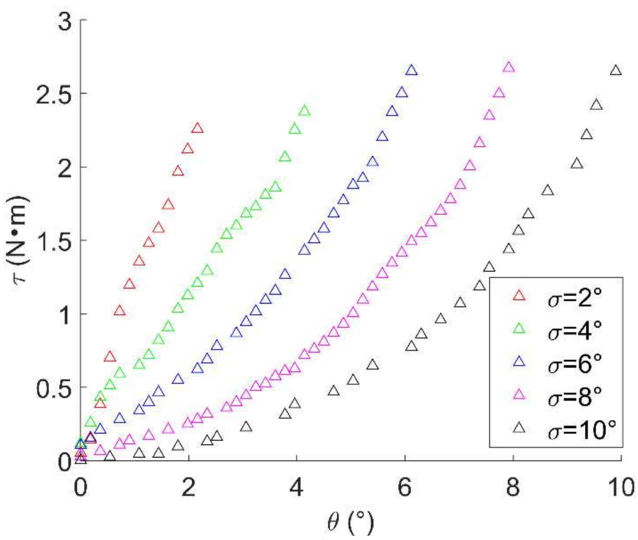
III. Analysis and Experiment

In the structural design of the core module, the shape of the cam surface and its stress are not considered. The core module may be seriously damaged in the normal movement process or sudden situation of the joint. Therefore, it is necessary to carry out stress analysis and strength check on the weak part of the joint. This chapter. This paper mainly analyzes the characteristics of the joint, and checks the strength of the weak link of the joint, so as to improve the whole joint. The structure of the joint ensures the normal operation of the joint.

Fig. 5 shows the stress analysis of few critical structures. Aluminium 6061 alloy is selected as the material for the prototype, which is enough for this application. The ultimate tensile strength is 124mpa, bending ultimate strength is 228mpa, elastic coefficient is 68.9gpa, Poisson's ratio is 0.330. SolidWorks is used for stress analysis and simulation. Under the external force of 400N, the two key parts do not exceed the



(a)



(b)

Fig. 6 (a) Experiment setup. (b)Experimental data corresponding to different values of relative angle of surfaces.

maximum bearing range, which means that both parts can withstand a torque of 5N•*m*.

The experimental platform is built as follows: the input shaft is fixedly connected with the base, and the output shaft is installed with a pressure sensor through the additional structure of 3D printing, as it shown in Fig. 6(a). The experiment takes five different values of relative angle of surfaces (σ), which are 2°, 4°, 6°,8° and 10° respectively. It can be seen from Fig. 6(b) that the output torque increases with the θ, and the average siffness decreases with σ. When σ is closed to 0, the output torque increase rapidly, the average stiffness is around 60 N•*m*/*rad*, in pace with the increase of σ, the average slope of the output characteristic slows down and the average stiffness is becoming smaller gradually.

IV. CONCLUSION

This paper presents a design of variable stiffness series mechanism, which is mainly through the cam disc-roller-spring system to achieve the change of stiffness. Then the system's transmission scheme is determined, the belt pulley is used for acceleration and deceleration, and the stiffness is changed by wire transmission. Strength check of key components are carried out, and build a prototype preliminarily. Conducted a preliminary static variable stiffness experiment, which verified the feasibility of variable stiffness, and the future work is to conduct theoretical analysis and control of the structure.

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