Variable Stiffness Actuator Structure for Robot

Chuanyi Cui[1,2], Kai Guo[1,2](✉), and Jie Sun[1,2]

[1] Key Laboratory of High-Efficiency and Clean Mechanical Manufacture, National Demonstration Center for Experimental Mechanical Engineering Education, School of Mechanical Engineering, Shandong University, Ji'nan 250061, People's Republic of China
kaiguo@sdu.edu.cn

[2] Research Center for Aeronautical Component Manufacturing Technology and Equipment, Shandong University, Ji'nan 250061, People's Republic of China

Abstract. Based on the idea of regulating the variation on stiffness by controlling the number of springs involved in the work, this paper designs a kind of variable stiffness actuator (VSA) which can be applied to the field of robot. The variable stiffness structure takes the spiral tensile spring as the elastic element, and the number of springs Participating in the work is controlled by the push-pull electromagnet. It has the accurate positive and negative 32 kinds of stiffness adjustment values. The structure model was established by using SolidWorks. MATLAB analysis was used to optimize the design of the structure and conduct mechanical and structural stiffness analysis, and the angle range and stiffness range of the actuator were obtained, which had showed a uniform characteristic of distribution of adjustable stiffness values in stiffness range interval. The conclusion is that the VSA has the advantages of real-time and accurate change of stiffness, wide variation range of stiffness and wide adjustment range of angle.

Keywords: Variable stiffness · Actuator · Robot

1 Introduction

Research for VSA has received wide-spread attention [1]. People study the design of VSA because it can minimize the impact on excessive force, realize human-machine interaction safely [2]. Researchers further hope that energy can be stored as intending in the elastic element and release to achieve the goal of saving energy. Currently, various VSA structures are designed, such as Series Elastic Actuators (SEAs) [3–6], Parallel Elastic Actuators (PEAs) [7] and serial-parallel elastic actuator (SPEA) [8, 9]. Sugar developed an actuator based on the principle of balance control stiffness [10], in which a linear spring was connected to the rigid actuator in series, and the force or stiffness required was controlled by changing the balance position of the spring. This design realizes a wide range of stiffness adjustment, but the complex transmission mechanism would lead to excessive volume and weight, which is unfavorable to the robot that needs flexible movement. Migliore et al. studied a device based on the principle of antagonistic control of stiffness [11]. Such a structure requires two series or parallel actuators with elastic elements to work against each other to control the position and

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stiffness at the same time [12, 13]. The output position is usually controlled by the differential motion of two actuators in the same direction and opposite direction to meet its compliance adjustment [14–16]. However, this setting has obvious limitations, including high energy consumption caused by complex coupling control and continuous control. The controlling method of stiffness of Jack spring structure adopted by Hollander et al. was to increase or decrease the number of effective spring coils by rotating the spring coil, thus changing the effective stiffness of the structure [17]. This structure can easily change the stiffness presupposition. But its narrow stiffness adjustment range is a significant limitation. Y. Xu et al. developed a new VSA with S-shaped Springs [18–20], their new VSA has excellent performance. They could change the stiffness by adjusting the amount and the angle of the S-shaped Springs, but they did not concern the fatigue of the springs designed. Wolf et al. from the German Aerospace Center developed VS-Joint [21], which can change the vertical position of the slider on the spring base by driving the spindle rotation of a small motor, so as to realize the adjustment of the stiffness. There is another way like the actuator with adjustable stiffness (AwAS) [22], a pseudo-linear variable-ratio lever variable-stiffness actuator (PLVL-VSA) [23], or the serial variable stiffness actuator II (SVSA-II) [24], which regulates the stiffness by change the transmission ratio between the output and elastic element. These studies have many applications for the interaction between robots and the environment, such as exoskeleton [22], rehabilitation robots [23], hopping robots [24].

Although the current VSAs have achieved suitable performance, they still face a common fundamental limitation, namely the fixed spring constant of the elastic element. The performance of traditional VSA is largely dependent on the spring constant. Yu Haoyong from the National University of Singapore mentioned in his paper [25] that soft springs can produce high-fidelity force control with low output impedance and reduced static friction, but it also limits the allowable force range and force control bandwidth of the system when it is subjected to a strong force. Hard springs, on the other hand, can increase the bandwidth of a force but reduce its fidelity. In order to achieve the desired output force/torque, most traditional VSAs are designed with very stiff springs, resulting in poor force control, low fixed compliance, poor reverse drive capability, and heavy systems.

In this paper, the motor is no longer simply used to control the change of a single or single kind of elastic element. A control method is used to design a VSA, which controls the exact change of stiffness by controlling the number of elastic elements involved in the work. The structure of this paper is as follows. Section 2 describes the structure design of the VSA, including principal designed parameters and working principle of important structures, and the establishing of the model with SolidWorks. Section 3 introduces the mechanical calculation and MATLAB simulation with analysis. Section 4 presents the stiffness analysis of the VSA, using MATLAB to get its angle range and stiffness adjustment range. Finally, the conclusions are shown in Sect. 5.

2 Structure Design

The VSA structure designed in this paper is mainly composed of movable rod, tensile spring, mesh chip, fluted disc, electromagnet, output disc and reset spring, as shown in

Fig. 1 below. When the VSA structure works, the current is input into the electromagnet, the electromagnet pushes the movable rod, so that the mesh chip fixed on the movable rod is embedded in the fluted disc, which is connected with input shaft. Then the fluted disc drives the movable rod to rotate, so that the corresponding tensile spring participates in the work to change the overall stiffness of the VSA, and to transfer the input shaft torque to the output disc; When the current stops input, the core of electromagnet moves back, then the movable rod is pushed back by the reset spring, the mesh chip is separated from the fluted disc, and the corresponding tensile spring disengages.

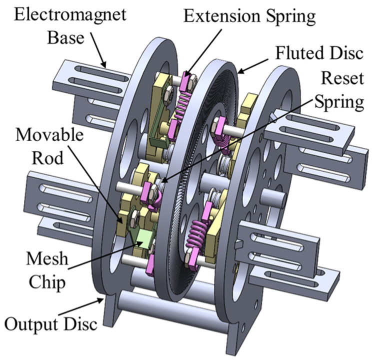


Fig. 1. VSA structure modeled by SolidWorks.

2.1 Principal Designed Parameters

Four kinds of tensile springs of SUS304-WPB materials with different stiffness were selected as elastic components, and their properties are shown in Table 1 below. The selection of springs designed in this paper is limited to prototype production in order to demonstrate the performance of VSA structures.

Table 1. Parameters pf SUS304-WPB spring with 4 different stiffnesses

Number	D (mm)	D (mm)	L (mm)	N	G (kgf * mm^{-2})	ki(g * mm^{-1})
1	0.5	5	15	10	7000	75.02
2	0.4	4	15	10	7000	60.01
3	0.3	4	15	10	7000	17.49
4	0.3	3	15	10	7000	45.01

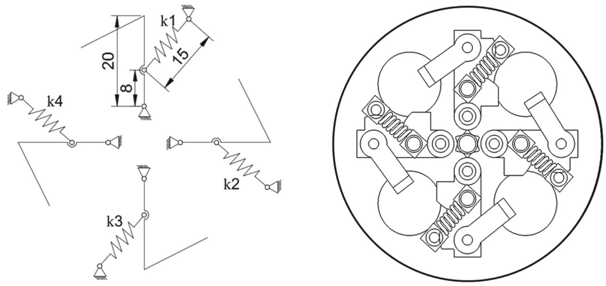
Inside the Table 1, the stiffness (spring constant) is expressed as ki (i = 1, 2, 3, 4). Spring stiffness calculation formula (unit: kgf/mm): $k = (G * d^4)/(8 * Dm^3 * Nc)$;
G: Rigidity modulus of wire rod;

L: Length;
d: Wire diameter;
D: Outside diameter;
Dm: Medium diameter = Outer diameter - Wire diameter;
N: Total number of coils;
Nc: Valid number of coils = total number of coils - 2;

2.2 Structure Design of VSA

The idea of the VSA structure is that the driving stiffness can be adjusted at any time. Through the work of each part and the division of mutual cooperation, the VSA structure designed in this paper can be divided into rod-spring structure, chip-disc structure and electromagnet propulsion structure.

Rod-Spring Structure. The 4 movable rods are connected with the output disc, conducting single directional rotating motion on the output disc. An end of the spring is fixed with the movable rod, and the other end is fixed on the output disc. The structure of the rod-spring is shown in Fig. 2 as follows.



(a) (b)

Fig. 2. The (a) is the Schematic diagram of rod-spring; (b) is the SolidWorks simulation model.

Chip-Disc Structure. The mesh chips are fixed on the movable rod to support the connection or disconnection between the rod-spring structure and the fluted disc. The fluted disc is connected with the torque input shaft, and the front and back of the fluted disc is respectively provided with a ring of fluted grooves for inserting the mesh chips.

Electromagnet Propulsion Structure. Electromagnet propulsion structure of the design of this paper is equivalent to the role of "switch". When the rated current signal is input into the electromagnet, the electromagnet will push the movable rod; When there is no current signal input to the electromagnet, the rod-spring structure will be reset. The structural schematic diagram is shown in Fig. 3.

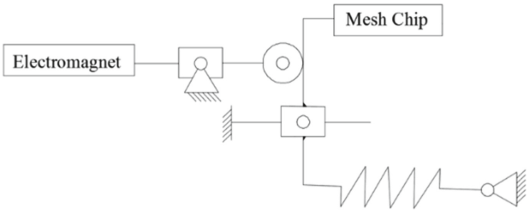


Fig. 3. Schematic diagram of the Electromagnet propulsion structure.

3 Mechanical Analysis

Tensile spring and movable rod connection diagram is shown in Fig. 4. Below. It has presented that when the springs participate in the work, they will transform the pull force into the moment. So every spring need to transform its stiffness ki, which is related to their own force and displacement, into stiffness Ki, which is related to torque and angle. The value of Ki is the stiffness spring of ki provides for VSA. The purpose of the mechanical analysis is to obtain the stiffness Ki of the VSA provided by the four kinds of tensile springs after they respectively participate in the work through mechanical and geometric calculation.

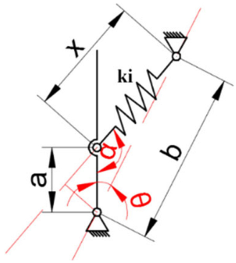


Fig. 4. Schematic diagram of connection between tension spring and movable rod.

When the movable rod is upright, x is original length of the spring, a is the distance between the connection point of the movable, from the law of cosines

$$x^2 = a^2 + b^2 - 2ab \cdot cos\theta \tag{1}$$

The b is the distance between the connecting point of the movable rod on the output disc and the fixed end of the spring on the output disc.

According to Hooke's Law, there is a spring tension force

$$F_i = k_i \Delta x \tag{2}$$

According to the law of cosines

$$x = \sqrt{a^2 + b^2 - 2ab \cdot cos\theta} \tag{3}$$

According to the law of sine

$$\frac{b}{sin\alpha} = \frac{x}{sin\theta} \tag{4}$$

$$sin\alpha = \frac{b \cdot sin\theta}{x} \tag{5}$$

The moment provided by the spring tension to the VSA is

$$M_i = a \cdot sin\alpha \cdot k_i \Delta x \tag{6}$$

$$M_i = \frac{k_i ab \cdot sin\theta}{x} \cdot \Delta x \tag{7}$$

Plug (3) into, then get

$$\Delta x = \sqrt{a^2 + b^2 - 2ab \cdot cos\theta} - \sqrt{a^2 + b^2 - 2ab \cdot cos\theta_0} \tag{8}$$

$$M_i = k_i ab \cdot sin\theta \cdot (1 - \frac{\sqrt{a^2 + b^2 - 2ab \cdot cos\theta_0}}{\sqrt{a^2 + b^2 - 2ab \cdot cos\theta}}) \tag{9}$$

The unit of moment M is g * mm.

From MATLAB simulation, the curve of the moment M on π/6–π/2 is shown below as Fig. 5.

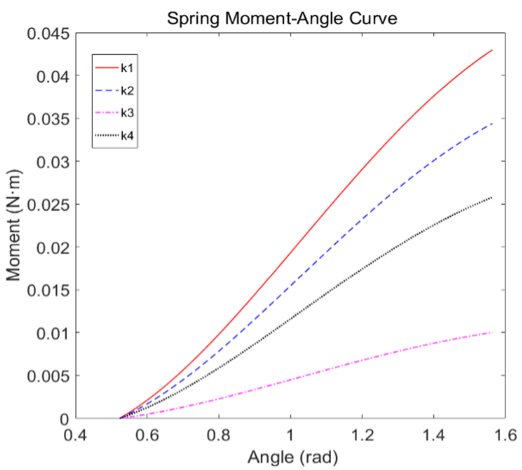


Fig. 5. The curve of M-Angle of 4 springs with different stiffness on π/6–π/2

It can be seen that the Moment-Angle curve has a good linearity. If the relationship between moment and angle is set as a linear one, there is

$$M_i = K_i\theta + C_i \tag{10}$$

Where, K_i is the stiffness of spring i converted into the overall stiffness of VSA, that is, the stiffness spring i can provide for the VSA, and the unit is N·m·rad^{-1}. Since the angle starts at π/6, the constant C_i can be abandoned, then (10) becomes

$$M_i = K_i\theta \tag{11}$$

Divide 0–π/3 into 9 equal parts, take 10 points (Fig. 6).

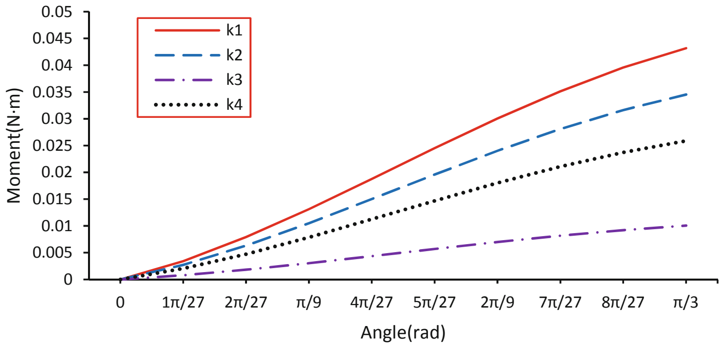


Fig. 6. The 9 bisected line chart of M-Angle of 4 springs with different stiffness on π/6–π/2

It can be seen from the above formula (9), spring stiffness of ki is directly proportional to the relationship of the moment Mi, so the single spring stiffness ki is also directly proportional to the relationship of its corresponding conversion Ki for. So, in the design of elastic element, this nature will be greatly convenient when users choose the spring stiffness and do the simulation calculation to obtain the desired adjustable stiffness value.

4 Stiffness Analysis

The stiffness of the VSA has two situations: clockwise and counterclockwise (positive and negative). In both cases, the adjustable stiffness is equal in size but opposite in direction. Therefore, the VSA designed has 16 different combined stiffnesses in each direction obtained by MATLAB simulation calculation.

5 Conclusion

Based on the concept of controlling the variation on stiffness by changing the number of elastic elements involved in the work, this paper designed a variable stiffness actuator which can be applied to the field of robot. A prototype was modeled on SolidWorks and its mechanical properties and stiffness were analyzed and simulated by using MATLAB. The VSA has the advantages of real-time and accurate change of stiffness, wide variation range of stiffness and wide adjustment range of angle. Due to the limitation of elastic elements, the VSA structure and control still has room for improvement, and the stiffness data can be further optimized. In the future, prototype will be made, and further experiments will be conducted on the control aspect based on this paper, and more data will be collected for optimization.

Although VSAs have many advantages, they still have many limitations, such as the need for more complex control algorithms. Researchers have made some progress in areas of adaptive tracking control [26, 27], neural networks [28], friction compensation [29] and other control algorithms, as well as dynamic joint stiffness identification and appropriate posture selection [30]. Therefore, structural design that can simplify the control algorithm and obtain more accurate control of velocity, force and position is also a direction of future work.

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