Structure and function of one-dimensional two-way pneumatic flexible bending joint

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Abstract: In order to solve the problems of comprehensive flexibility of robot arm, and expand the application field of service robot and improve the safety, a one-dimensional two-way flexible bending joint is developed by using the self-developed pneumatic artificial muscle. The relevant theoretical model is established and the relevant experimental analysis is carried out. The experimental results show that the bending joint can realize one-dimensional two-way bending motion and the bending angle of the joint can be controlled by adjusting the gas pressure; when the air pressure difference between the two sides of the leaf spring is 0.22Mpa, the maximum bending angle of the joint reaches 74.12 degrees; the forward and reverse bending of the joint are consistent, and the joint bending curve is similar to the arc.

1. Introduction
Due to the progress of science and technology and the aging of society, a large number of service robots are needed in medical, family service, business and other service industries, which can replace human beings to complete service functions. Robot arm is the key executive component of all kinds of service robots. At present, most of the robots are lack of comprehensive flexibility in structure, motion, drive and control, which is difficult to meet the requirements of safety, flexibility and adaptability of service robots. At present, the flexible manipulator mainly has three forms: rope drive¹², functional material drive³ and artificial muscle drive⁴⁶. The rope is easy to relax in the work, and the deformation of functional material is small. In this paper, a one-dimensional bi-directional flexible bending joint is developed by using the self-developed pneumatic artificial muscle, which is compact in structure, flexible in structure and flexible in motion.

2. Structure and function
The one-dimensional two-way pneumatic flexible bending joint is mainly composed of the upper end cover, the lower end cover, the restraint plate, the plate spring and the artificial muscle (figure 1). The artificial muscle is a closed cavity formed by an elastic air bag, an upper and a lower plug. A group of restraint rings with the same structure are set on the outside. The two ends are constrained by the upper and lower covers. A rectangular hole is set in the middle of the restraint ring for installing the plate spring. The artificial muscle on one side of the leaf spring is filled with pressure gas, and the inner wall is compressed and expanded. Due to the restraint effect of the external restraint plate, the radial deformation of the artificial muscle is limited, and the axial force of the artificial muscle is...
generated. Because of the axial restriction of the end cover and the leaf spring, the joint realizes the bending function.

![Joint 3D model and motion diagram](image1)

**Figure 1. Joint 3D model and motion diagram**

### 3. Joint theory model

When the joint works, the lower end cover is fixed, and under the action of gas pressure, the artificial muscle drives the upper end cover to realize bending. When the joint is bending forward, it can be seen from the moment balance (figure 2):

$$2M_P = M_K + 2M_n' + 2M_n''$$  \hspace{1cm} (1)

Where, $M_P$ is the driving torque of the artificial muscle to the joint end cap under the air pressure; $M_k$ is the resistance moment produced by the leaf spring; $M_n'$ is the impedance moment produced by the left artificial muscle; $M_n''$ is the impedance torque produced by the right artificial muscle.

![Analysis of joint torque](image2)

**Figure 2. Analysis of joint torque**

When the artificial muscle is bent, the deformation of the outer diameter of the airbag can be ignored under the action of the restraint ring, the wall thickness of the outer side of the airbag is thinner, and the wall thickness deformation of the side contacting with the plate spring can be ignored. The geometric relationship of the joint bending deformation is shown in figure 3.

The driving torque at the joint end cover is:

$$M_P = \Delta P e \left( \frac{D_1^2 e \theta + D_2^2 l_0}{4l_0 + e \theta} \right)$$  \hspace{1cm} (2)

Where, $\Delta P$ is the pressure difference between the artificial muscles on both sides of the leaf spring; $D_1$ is the outer diameter of the elastic airbag; $D_2$ is the inner diameter of the elastic airbag; $l_0$ is the original length of the elastic airbag; $e$ is the distance from the axis of the elastic airbag to the central line of the leaf spring; $\theta$ is the bending angle of the joint.

The resistance moment of the leaf spring is:
\[ M_n = \frac{Ebh^3\theta}{12l_0(1 - \mu^2)} \]  

Where \( E \) is the elastic modulus of the plate spring material; \( \mu \) is Poisson's ratio; \( b \) is the width of leaf spring; \( h \) is the thickness of the leaf spring.

In the process of bending, the artificial muscle will produce its own deformation resistance, and the impedance torque produced by the left artificial muscle will be smaller is:

\[
M' = \frac{D^4 E_1 \pi \theta}{64(l_0 + e \theta)} - E_1 \pi \theta \left( \frac{D^2 e \theta + D_0^2 l_0}{64(l_0 + e \theta)^2} \right) + \frac{D_0^2 e^2 E_1 \pi \theta}{4(l_0 + e \theta)} - \frac{e^2 E_1 \pi \theta(D^2 e \theta + D_0^2 l_0)}{4(l_0 + e \theta)^2}
\]

Where, \( E_1 \) is the elastic modulus of the elastic airbag.

The artificial muscle on the right side is compressed and the deformation is uncontrollable, through the experimental data fitting:

\[ M_n = a + bP + c\theta \]  

Where, \( a = -0.008, b = 0.183, c = -0.059 \)

Substituting formula (2), (3), (4), (5) into formula (1), the following results are obtained:

\[
2\Delta P e^\frac{\pi}{4}\left( D_0^2 e \theta + D_0^2 l_0 \right) = \frac{Ebh^3\theta}{12l_0(1 - \mu^2)} + \frac{D_0^2 E_1 \pi \theta}{32c(l_0 + e \theta)} + \frac{e^2 E_1 \pi \theta(D^2 e \theta + D_0^2 l_0)}{32c(l_0 + e \theta)^2} + a + bP + c\theta
\]

4. Joint kinematics experiment

4.1 Experimental study on the angle of joint bending

The experimental principle of joint bending angle is shown in figure 4. During the experiment, the lower end cover of the joint is fixed, and the bending angle of the joint under different air pressure is obtained through the gyroscope installed on the upper end cover (figure 5). It can be seen from the figure that when the air pressure difference between the two sides of the leaf spring is 0.22MPa, the forward bending angle of the joint reaches 74.12°. Through the comparison between the pressure relief curve and the pressure charging curve, it is found that the pressure relief curve has a certain lag, which is mainly due to the lag of elastic airbag rebound.

![Figure 4. Schematic diagram of joint bending angle experiment](image)

![Figure 5. Curve of joint bending angle and air pressure](image)
4.2 Joint pressure and deformation experiment
Eight marker points were fixed on the joint at equal intervals. Using the experimental system shown in figure 6, the deformation of the joint under different air pressures was obtained by using the 3D capture system (NDI Optotrak type). The pressure range was 0 ~ 0.2MPa, and the pressure interval was 0.04MPa. It can be seen from figure 7 that the forward and reverse bending of the joint have good consistency, and the bending curve of the joint is approximate to the arc.

Figure 6. Schematic diagram of joint deformation experiment

Figure 7. Curve of joint forward and reverse bending deformation and air pressure

5. Conclusion
A one-dimensional bi-directional flexible bending joint is developed by using the self-developed pneumatic artificial muscle, which has compact structure, good structural flexibility and motion flexibility, and the plate spring is set in the middle position to ensure the flexibility of the joint and improve the stiffness of the joint body. The structure and working principle of the bending joint are described. The relevant theoretical model is established and the experimental analysis is carried out. The results are as follows:

1) The bending joint can achieve one-dimensional and two-way bending motion, and the bending angle of the joint can be controlled by adjusting the pressure of the gas;

2) When the air pressure difference between the two sides of the leaf spring is 0.22mpa, the bending angle of the joint reaches the maximum value of 74.12 °;

3) The forward and reverse bending of the joint are consistent, and the joint bending curve is similar to the arc.

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