A new type of pneumatic linear reciprocating actuator

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Abstract. A new type of pneumatic linear reciprocating actuator based on the Sarrus mechanism is presented in this paper, which includes an external rigid deployable frame, and an internal flexible foldable bellows-type airbag, and a set of rubber bands. The actuator has advantages of large stroke, small volume, large expansion ratio, and elongation which can be controlled by air pressure. It can achieve reciprocating linear motion with a larger expansion ratio of 800%. This paper first introduces the structure of the rigid frame and airbag, and introduces the manufacturing process of the airbag under laboratory conditions. Then, the theoretical analysis of the actuator is carried out, and the air pressure displacement characteristic formula is introduced. Finally, the correctness of the characteristic curve is verified by experiments.

1. Introduction

The pneumatic cylinder is the most common linear reciprocating actuator. Due to its structural reasons, the expansion ratio of single-acting cylinder is always less than two [1]. The multi-stage telescopic cylinder solves the problem of low expansion ratio, but its cylinder volume is large. The Bellows actuator is a flexible linear reciprocating driver invented by Pridham DC in 1967[2]. The bellows actuator has an elastic airbag, which contains folds perpendicular to the longitudinal axis. Belforte G et al. conducted theoretical modeling analysis and experiment on this bellows actuator [3]. An extensible pneumatic actuator with bellows (EPAB) is proposed in [4]. It consists of a rubber tube and a highly packed bellows sleeve which has an unloaded strain of up to 350%. A multi-material PolyJet printable linear bellows actuators are presented in [5]. This kind of bellows-type actuator has the advantage of large deformation, but the disadvantages are that the axial stiffness is low. And it needs to use the material's elasticity to reset, so the wall thickness of the bellows is generally large, resulting in a large thickness in the contracted state. Sarrus mechanism is a spatial mechanism that transforms the finite circle motion into a straight line motion with a degree of freedom of 1 [6]. The Sarrus mechanism has the advantages of simple and reliable and strong bearing capacity. As a unique spatial mechanism, it is gradually gaining attention and application. O’Brien et al. applied it to the design of collapsible tables and chairs, saving the use of space, increasing the portability of tables and chairs [7]. Liao Bo et al. used the Sarrus mechanism to design the robotic arm, which expanded the working space of the robotic arm so that it could adapt to more working environments [8]. The research on the Sarrus mechanism usually regards it as a kind of expandable mechanism frame with a large expansion ratio, but its driving method does not use a flexible driver, so the characteristics of its large expansion ratio are largely wasted. This paper proposes a new type of pneumatic linear reciprocating actuator that combines the advantages of a single-acting cylinder, a bellows flexible driver, and a Sarrus mechanism. It has the advantages of small size, large expansion ratio, strong bearing capacity, and controllable displacement.
2. Overall structure

2.1. Structure and principle
The new pneumatic linear actuator structure is mainly composed of three parts: an expandable frame based on the Sarrus mechanism, an internal flexible bellows-type foldable airbag, and a set of elastic rubber bands, as shown in Fig. 1.

![Actuator structure](image1)

Figure 1. Actuator structure

Its working principle is that when the compressed air is connected to the driving airbag, the pressure of the compressed air overcomes the elastic force and load, and the rigid frame and the rubber bands are stretched. When the pressure of the compressed air is reduced, the rigid frame is contracted to its original state by the elastic force of the rubber bands, as shown in Fig. 2. By controlling the ventilation and degassing of the airbag, the rigid frame reciprocates linearly.

2.2. Structural design of rigid frame

The rigid deployable frame is based on the Sarrus mechanism. It consists of an upper plate, a lower plate, and 4 pairs of side connecting rods. The upper and lower connecting rods are the main transmission components and play the role of connecting the upper and lower bottom plates. The design of the connecting rod adopts the axis offset method so that the rod can be fully compressed and completely straightened, which also ensures that the actuator has a large expansion ratio. The upper and lower plates
are provided with slots for storing the upper and lower connecting rods. The purpose of this embedded design is to completely hide the internal structure and details when contracting.

![Figure 3](image)

**Figure 3.** Parameters of contraction state

### 2.3. Analysis of expansion ratio of rigid frame

In the deployable mechanism, the expansion ratio is one of the most important parameters. The expansion ratio is the ratio of the expansion height of the mechanism to the folding height. The influence of the structural parameters of the Sarrus mechanism on the expansion ratio is analyzed below.

The contracted state of the actuator is a flat rectangular cuboid with a square bottom, as shown in Fig. 1. The side length of the square is $a$, the minimum height of the actuator is $h$, and the thickness of the housing is $t$; the center distance between the two holes of the connecting rod is $L$, its horizontal projection length is $l$, the connecting rod width is $w$, and the connecting rod thickness is $d$.

Based on the geometric relationship of the initial states, the following formula is obtained.

$$a = l + 3t + 1.5d + w$$  \hspace{1cm} (1)

$$h = 2d + 2t$$  \hspace{1cm} (2)

$$L = \sqrt{l^2 + d^2} / 4$$  \hspace{1cm} (3)

When the rotation angle is $\theta$, the relationship is as follows:

$$H = 2L\sin \theta + d + 2t$$  \hspace{1cm} (4)

Based on the above formula, the expansion ratio is obtained:

$$\eta = \frac{H}{h} = \frac{2L\sin \theta + d + 2t}{2d + 2t}$$  \hspace{1cm} (5)

When $\theta = 90^\circ$, the frame is at the limit position and has the maximum expansion ratio:

$$\eta_{\text{max}} = \frac{2L + d + 2t}{2d + 2t}$$  \hspace{1cm} (6)

Due to the slenderness of the rod, the angle between the centreline of the two holes and the horizontal line is approximately equal to $0$, and the center distance and its projection in the horizontal direction can be regarded as equal. That is, $L = l$. For the symmetry and stability of the structure, and the section of
the side connecting rod is designed as a square, so \( w = d \); at this time, the expansion ratio formula can be simplified as:

\[
\eta = \left(\frac{2l + d + 2t}{h}\right)
= \left(\frac{2a - 6t - 3d - 2w + d + 2t}{h}\right)
= \left(\frac{2a - 4t - 4d}{h}\right)
= \frac{2a}{h} - 2
\]  

(7)

It can be seen that the expansion ratio of Sarrus mechanism is positively related to the square side length of the contraction cross-section, and negatively related to the initial height, and has nothing to do with the thickness of the shell. The actual design takes \( a = 80\text{mm} \) and \( h = 16\text{mm} \), so the expansion ratio is 800\%, which is a very large expansion ratio.

3. Airbag structure design and manufacturing process

3.1. Airbag structure

The structure of the flexible foldable drive airbag is shown in Fig. 3. The airbag structure includes an air inlet, an upper plate, an airbag body, and a lower plate. The main body of the airbag is formed by connecting a series of small airbags with a square cross-section. Adjacent airbags are connected by gluing, and there are holes in the gluing surface. The air inlet is used to inflate the airbag, and the upper and lower plates are respectively connected to the upper and lower platforms of the rigid frame.

![Figure 4. Airbag structure](image)

3.2. Airbag manufacturing process

At present, there is no such kind of flexible foldable airbag manufacturer in the market. The manufacturing process of the flexible foldable airbag is briefly introduced. The materials used include aluminum plastic film (APF), circular double-sided adhesive tape and so on. The tools used include heat sealing machine, laser cutting machine, and whole puncher and so on.

- Cutting - Use a laser cutting machine to cut the APF into a suitable square block.
- Heat sealing - Use the heat sealing machine to seal the four sides of the two pieces of APF into a sealed bag. For the following the punching procedure, keep one of the bags unsealed.
- Gluing - Use circular double-sided adhesive to connect several sealed bags with an unsealed aluminum plastic bag at the bottom.
- Punching – Put the unsealed bag at the bottom, then use a whole puncher to punch a hole in the center of the series airbags except the unsealed one.
- Sealing - Seal the unsealed airbag with the heat sealing machine.
- Assembling - Use circular double-sided adhesive to glue the upper and lower plates and the airbags together and install the gas pipe.
Figure 5. Airbag manufacturing process

In this way, a flexible foldable bellows-type airbag is manufactured by hand. Under the existing laboratory conditions, the advantages of the technology are simple and cheap.

4. The theoretical model of the actuator

In the steady-state, as shown in Fig. 6, the upper plate is balanced by the load force (including the gravity term) and the elastic force of the rubber bands and the driving force of the airbag.

\[ F_p = 2nF_s + F_g \]  

(8)

Where, \( n \) is the number of rubber bands.

Figure 6. A schematic view of the force analysis
The driving force of the airbag is:

\[ F_p = PS \]  

(9)

Where, \( P \) is the air pressure inside the airbag, and \( S \) is the contact area. Further, in the single airbag model, the following three hypotheses are proposed in order to simplify analysis.

(a) The shape of the airbag cross-section is a rounded rectangle.
(b) The circumference of the airbag cross-section is constant.
(c) The contact surface of the airbag is square.

Based on the above assumptions, the following inference can be obtained. If the length of the original side of the airbag is \( b_0 \), the length of the contact surface is:

\[ b = b_0 - \pi r \]  

(10)

The fillet radius of cross-section is:

\[ r = d / 2 \]  

(11)

The height of a single airbag is:

\[ d = H / m \]  

(12)

Where, \( m \) is the number of stacked airbags.

The area of contact surface is:

\[ S = b^2 \]  

(13)

Combining the above formulas, we can get:

\[ S = (b_0 - \pi H / 2m)^2 \]  

(14)

Considering the stiffness coefficient of the rubber band is \( k \), the original length of the rubber band is \( x_0 \), and the installation length is \( a \), and the installation width is \( h \), the elasticity produced by a single rubber band when displacement equals \( x \) is:

\[ F_s = k(2x + 2a + 2h - x_0) \]  

(15)

\[ H = H_0 + x \]  

(16)

Based on the above formulas, it is concluded that:

\[ P = \frac{2nk(2x + 2a + 2h - x_0) + F_s}{(b_0 - \pi(H_0 + x) / 2m)^2} \]  

(17)

Where, \( n \) is the number of rubber bands, \( k \) is the stiffness coefficient of a rubber band, \( m \) is the number of stacked airbags, \( x \) is actuator’s displacement, and \( H_0 \) is the initial height of the airbag.
This formula reflects the relationship between the displacement of the actuator and the required air pressure, and it is important for controlling the displacement of the actuator. The understanding of the characteristic curve is that the initial contact area is large, the required air pressure is small, the later contact area becomes smaller, the required air pressure increases, and there is a limit displacement which makes the air pressure too large to reach that position. Mathematically, the pressure displacement characteristic curve is a hyperbola, and the undefined point is when its denominator is zero.

\[ b_0 = \pi(H_0 + x) / 2m \quad (18) \]

\[ x = 2mb_0 / \pi - H_0 \quad (19) \]

The actual physical meaning is that a single airbag has become a sphere, so it cannot reach the position.

5. Pressure displacement experiment

The experiment platform built with scale, air pump, and pressure relief valve with digital display is shown in Fig. 7. When the load is 0kg, 1kg respectively, adjust the outlet pressure of the pressure reducing valve, inflate the actuator. Record the displacement of the free end of the actuator under different air pressure to obtain the pressure displacement curve, as shown in Fig. 8.
As shown in the diagram, the experimental results show that when the inflation pressure is increasing, the axial displacement of the actuator is nonlinear, and with the increase of air pressure, the displacement increases, and no longer changes after reaching the limit position. The experimental data and the theoretical curve have the same trend, but there is a fixed offset, which is caused by ignoring the friction and gravity of the system with the theoretical formula. If the friction is considered, the experimental data will fit the theoretical curve very well, which shows that the theoretical formula is reasonable.

6. Conclusion

The new type of pneumatic linear reciprocating actuator proposed in this paper is based on the Sarrus mechanism, which has the characteristics of small volume and large expansion ratio. The relationship between the expansion ratio and the mechanical parameters is introduced. A bellows-type airbag is designed, and its manufacturing process is introduced. The airbag is inelastic, so the thickness is very small. The formula of air pressure displacement characteristics is obtained through modeling, and its correctness is verified by experiments. It can replace the traditional cylinder when it requires small size, large stroke, and large expansion ratio. It has great potential application value.

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