Modeling of Extensible Pneumatic Actuator with Bellows (EPAB) for Continuum Arm

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Abstract—The ability of a continuum arm is influenced by the performance of an actuator. Although several extensible pneumatic actuators have been proposed in previous research, balancing strength with large strain is still a challenge. We propose an extensible pneumatic actuator with bellows (EPAB) that consists of a rubber tube and a highly packed bellows sleeve. We propose a parametric model of the EPAB that can comprise various bellows and rubber tubes. We measured the basic properties of four actuators with different parameters to verify the proposed model. We conducted evaluation experiments under two conditions: constant length with variable pressure and constant pressure with variable length. The experimental results indicate that the proposed model can roughly predict the measured data. The proposed extensible actuator has an unloaded strain of up to 350% at a pressure of 0.6 MPa.

I. INTRODUCTION

The objective of a continuum arm is to provide flexibility and dexterity to a robotic manipulator. Several types of continuum arms have been investigated, for example, OctArm[1][2] for grasping objects in the field and STIFF-FLOP[3][4] for surgical tasks. Although continuum arms are inspired by an elephant trunk and animal tentacles and tongues, their driving mechanisms differ. AirOctor[5][6] and KSI tentacle manipulator[7] use tendon cables and a pneumatically pressurized continuous backbone. There are a few issues associated with the guiding cable and friction loss when using tendon-driven arms.

Another approach employed for developing continuum arm [8] and soft fingers [9][10] is the use of extensible fiber-reinforced pneumatic actuators. An inverse pneumatic artificial muscle (IPAM)[11], which comprises a rubber tube with spiral fiber wrapping, can elongate up to 340% of its natural length. A pressurized bellows structure is also used for continuum manipulators[12][13][14]. The main disadvantage of these bellows and fiber-reinforced rubber tubes is that it can operate only at relatively low pressures, so as to prevent fatal expansion in the radial direction.

Pneumatic artificial muscle (PAM) can serve as an actuator, as well as a soft backbone[15]. The McKibben PAM consists of an inner rubber tube and a braided sleeve that covers the tube. The McKibben PAM is capable of functioning at large operational pressures owing to the crossed fiber sheath that is separated from the inner tube. The elongation of the McKibben muscle is achieved using the large initial angle of the crossed fibers of the sleeve, unlike the original McKibben muscle[16]. OctArm[1] employs the McKibben PAM in elongation mode. This extensor actuator provides a large strength-to-weight ratio. However, the elongation strain is limited to approximately 60% to 80% of its natural length. The McKibben actuator with a wrinkled braided sheath[17] has also been reported, but its elongation is limited to approximately 10%.

The main objective of this study is to develop an extensible pneumatic actuator that combines two requirements: a large elongation strain and a large operational pressure. We consider that the bending actuator proposed for wearable devices[18] indicates a promising direction. They generate rotary movements with a rubber tube covered with a bellows structure. We proposed an extensible pneumatic actuator with bellows (EPAB) that consists of a rubber tube covered with a pleated braided sleeve as a bellows structure. A design similar to the EPAB can be found in the Hydro Muscle [19]. Unlike our EPAB, the hydro muscle uses a spontaneous wrinkles of an inelastic fabric as an outer element.

The EPAB can be used for enhancing the performance of a continuum arm. There are only a few theoretical models of extensible pneumatic actuators with large deformation. We also develop a theoretical model to reveal the relationships between the form factors of the bellows and basic properties of the actuator.

This paper is structured as follows: In the next section, we introduce the basic principle of an extensible actuator and
describe a parametric model. We describe the experimental setup in Sec.III, and the results and discussion are described in Sec.IV and Sec.V, respectively. Finally, the conclusions of the study are provided in Sec.VI.

II. MODELING OF EXTENSIBLE PNEUMATIC ACTUATOR WITH BELLOWS

A. Overview

Figure 1 shows the relaxed and pressurized states of the actuator under no load. The actuator consists of an inner rubber tube and an outer bellows (Fig.2). When the inner rubber tube is pressurized, the highly packed pleats provide room for elongation in the longitudinal direction. The radial inflation is restricted by the bellows at the same time.

The bellows consists of a crimped braided sheath and is constructed in the following steps. First, we insert a steel rod into the braided sheath as a mandrel. Next, we compress the braided sheath in the axial direction to make frills and fix both ends to maintain the shape. Finally, we heat the sheath in an oven to memorize the shape. The bellows, air fittings, and a rubber tube are tied using stainless steel wires at both ends.

B. Modeling of bellows

We simplify the inner surface of the bellows as a cylindrical shape (Fig.3).

We also assume a linear relationship between the change in inner radius and the axial length of the bellows as follows:

$$ R = \frac{R_1 - R_0}{L_{b1} - L_{b0}} (L_b - L_{b0}) + R_0 $$  \hspace{1cm} (1)

Here, $R$ is the inner radius of cylinder, and $L_b$ is its axial length.

$R_0$ and $R_1$ are the inner radius of bellows when their axial lengths have the minimum value $L_{b0}$ and maximum value $L_{b1}$, respectively (Fig.3).

C. Modeling of rubber tube

The tension force of the actuator $F$ is a combination of the elasticity of the rubber tube and the pneumatic pressure:

$$ F = F_t - PS $$  \hspace{1cm} (2)

Here, $F_t$ is the tension force of the rubber tube, $P$ is the inner pressure of the rubber tube, and $S$ is the inner cross-sectional area of the rubber tube. Let the length, inner radius, and outer radius of the rubber tube be $L_r$, $r_i$, and $r_o$, respectively. We assume that the inner pressure in the radial direction has no effect on the elongation. Under this assumption, $F_t$ can be expressed as $F_t(L_r)$, a function of $L_r$ only.

The cross sectional area $S$ is calculated as follows:

$$ S = \pi r_i^2 $$ \hspace{1cm} (3)

Under the assumption of the volume of rubber is constant, the following equation is satisfied:

$$ L_{r0} \pi (r_{o0}^2 - r_{i0}^2) = L_r \pi (r_o^2 - r_i^2) $$ \hspace{1cm} (4)

Here, $r_{i0}$ and $r_{o0}$ are the inner and outer radii of the rubber tube in its natural length $L_{r0}$, respectively.

D. Modeling of whole actuator

Using Eqs.(3) and (4), the cross sectional area of rubber tube can be calculated as follows:

$$ S = \pi r_i^2 = \pi \left\{ r_o^2 - \frac{L_{r0}}{L_r} (r_{o0}^2 - r_{i0}^2) \right\} $$ \hspace{1cm} (5)

When the rubber tube is pressed to the bellows by inner pressure, the outer radius of the rubber tube is equal to the
inner radius of the bellows. Therefore, \( r_o \) is calculated using Eq.(1).

\[
r_o = R = \frac{R_1 - R_0}{L_{b1} - L_{b0}} (L_b - L_{b0}) + R_0 \tag{6}
\]

If the length of the actuator \( L \) is equal to the length of the bellows and the length of rubber \( (L = L_e = L_b) \), from Eqs.(5) and (6), \( S \) is the function of \( L \).

The tension force of actuator is represented as follows, based on the Eq.(2):

\[
F(P, L) = F_e(L) - PS(L) \tag{7}
\]

Under the following specific two conditions, we can rewrite Eq.(7).

1) \( P = \text{Const.} \): Substituting the constant \( P = C_3 \) into Eq.(7),

\[
F(L) = F_e(L) - C_3 S(L). \tag{8}
\]

2) \( L = \text{Const.} \): Substituting the constants \( F_e(L) = C_1 \) and \( S(L) = C_2 \) into Eq.(7),

\[
F(P) = C_1 - PC_2. \tag{9}
\]

III. EXPERIMENTAL SETUP

A. Materials

1) Bellows: We used a polyester sleeve with a maximum radius of 12 mm (NFL-12, Denka Electron Co. Ltd., Japan) and metal rods with diameters of 18 mm and 22 mm to make bellows from the sleeve. The oven temperature is set to 120°C to memorize the pleated shape.

2) Rubber Tube: Two types of latex rubber tubes were used:
   - Rubber A: New latex rubber tube (AS ONE Corporation, Japan)
   - Rubber B: VWR Amber Latex Rubber Tubing (NIPPON Genetics Co. Ltd, Japan)

   The inner and outer diameters of both the rubber tubes are 17 mm and 12 mm, respectively.

3) Assembly: The end connectors integrated with air fittings were made by a 3D printer. The diameter of the air supply tube is 6 mm.

B. Measurement

Figure 5 shows a custom-made experimental device. This device has a force sensor (FGP-100, Nidec-Shimpo Co., Japan), a length sensor (DS-025, Mutoh Engineering Inc., Japan), and lead screws driven by an electrical motor. Stainless steel wire ropes are attached at both ends of the actuator. One end is tied up with the force sensor, and the other end is attached to the base moved by the lead screws.

Actuators were evaluated under the following two conditions:

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Actuators were evaluated under the following two conditions:

1. \( P = \text{Const.} \): Relation between length and force at constant pressure

   The actuators were stretched from their natural length to a maximum length of 150 mm and then turned back continuously by using lead screws at a fixed pressure. We measured the tension force during the round trip. The pressure was varied from 0.0 to 0.4 MPa in increments of 0.1 MPa. We conducted this experiment five times for each actuator and calculated the mean values.

2. \( L = \text{Const.} \): Relation between pressure and force with constant length.

   The specific length of the actuator was fixed. Then, we measured the tension force when the actuator was pressurized and depressurized between 0.0 to 0.4 MPa continuously. The length was varied from 90 to 150 mm, in increments of 10 mm. We conducted this experiment once for each actuator.

IV. EXPERIMENTAL RESULT

A. Strain

We measured the maximum strain of the four different actuators under the no-load condition. The strain is defined as follows:

\[
\epsilon = \frac{\Delta L}{L_0} = \frac{L - L_0}{L_0} \tag{10}
\]

The results are summarized in Table I. The results indicate that the combination of the soft rubber tube (B) with the bellows with large pleats has a maximum strain of 376%.

B. Linear regression

We calculated \( F_e \) in Eq.(7) for each rubber tube. We derived the force-length relationships of the actuator under the no-pressure condition. Then, third-order linear regression was performed for the measured data.
Figure 6 shows the third-order linear regression results between the actuator length and force at a pressure of $P = 0$.

Based on this result, the force $F_r(L)$ (N) of the actuator consisting of rubber A can be expressed using the following formula:

$$F_{rA}(L) = 1.6 \times 10^5 L^3 - 3.8 \times 10^4 L^2 + 4.2 \times 10^3 L - 80 \quad (11)$$

whose length is $L$ (m), and that of rubber B is also expressed,

$$F_{rB}(L) = 1.3 \times 10^4 L^3 - 3.1 \times 10^3 L^2 + 8.0 \times 10^2 L - 7 \quad (12)$$

C. Prediction model

Based on the linear regression results, we can calculate the prediction models based on Eqs. (8) and (9). Figure 7 and 8 show the theoretical properties under the condition of $L = \text{Const.}$ or $P = \text{Const.}$.

D. Measurement

1) Constant pressure: Figure 9 shows the measured relationship between force $F$ and actuator length $L$ of the four actuators. The minimum length of the actuators, which is its natural length, is approximately 30 mm. The maximum length of the actuators is set to 150 mm. After several experiments, the natural length of the actuators becomes approximately 35 mm. The range of the force output of the actuators with rubber tube A is larger than that of the actuators with rubber tube B. Stiffer rubber tubes can produce a larger tension force. Actuators with bellows having small inner diameters $R_0 = 9$ have large hysteresis at $F = 0$.

2) Constant length: Figure 10 shows the measured relationship between the pressure and force of four actuators at constant length. The range of force (actuator $R_0 = 9$) is wider than that of $R_0 = 11$. Further, actuator $R_0 = 9$ has a larger hysteresis. Flat parts are observed at lower pressures, in particular, for actuator (rubber A).
Fig. 10. Under the condition $L = \text{Const.}(90 + 10 \times [0 - 6])$, the evaluated relationship between the force and length for each actuator: Left Up: $R_{0} = 18$, rubber:A. Right Up: $R_{0} = 22$, rubber:A. Left Down: $R_{0} = 18$, rubber:B. Right Down: $R_{0} = 22$, rubber:B.

Fig. 11. Comparison between experimental results (red) and model (blue) under the condition $P = \text{Const.}$, based on model and linear regression of the experimental results at $P = 0.0$ (MPa) Left top: $P = 0.1$ (MPa), Right top: $P = 0.2$ (MPa), Left bottom: $P = 0.3$ (MPa), Right bottom: $P = 0.4$ (MPa).

VI. DISCUSSION

In this section, we discuss the comparison between the components (inner radius of the bellows and rubber type) of the actuators with the model and hysteresis.

We can choose different rubber tubes depending on the desired force. After fitting $F_{r}$, the behavior of the actuator can be predicted roughly. For example, the model of actuator ($R_{0} = 11$ (mm), rubber:A) is shown in Fig. 11.

Next, we consider the above difference between the experimental results and model. We focus on three main aspects. The first aspect is the assumption of the linearity between the inner radius and the length of the bellows. Bellows in actual applications might be smaller than the assumed value because the measured force is smaller, as shown in Fig.11 and Fig.12. The second aspect is the constant volume of the rubber tube. The rubber tube should be compressible at high pressures, and there should be an interaction between longitudinal strain and transversal strain. In fact, the difference is higher at high pressures (see Fig.9). The third aspect is simplifying the shape of the bellows to a cylindrical form. It should have sufficient space for the rubber tube to extend in the radial direction because of the softness of the bellows. Therefore, the inner cross-sectional area must be larger than that in the model. However, they have an inverse relationship, as shown in Fig.11 and Fig.12. Thus, the shape of the bellows might have little influence.

We neglect the hysteresis of the rubber tube in the linear regression $F_{r}$. Instead, we observe the friction between the bellows and rubber tube. Actuators ($R_{0} = 9$ (mm)) have a larger hysteresis than actuators ($R_{0} = 11$ (mm)) (compare left and right column in Fig.9 and Fig.10). This might be caused by the larger friction between the bellows and rubber tube because a smaller inner radius of the bellows results in a larger normal force. For the same reason, the range of $F > 0$ in Fig.9 is larger than that predicted by the model (Fig.7).

VI. CONCLUSION

We developed a parametric model of an extensible pneumatic actuator with bellows (EPAB). We conducted experiments to compare the properties of actuators with different
values of the inner radius of the bellows and rubber tubes with different elasticities. The experimental results indicate that the proposed model can roughly explain the basic properties of the actuators with different parameters. The results also indicate that hysteresis has a large influence on required pressure to move the bellows structure. Future studies will focus on developing models including hysteresis and developing a continuum arm based on this model.

REFERENCES