Force and position control of the rubberless artificial muscle antagonistic drive system

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ABSTRACT

This paper describes the control of the rubberless artificial muscle antagonistic drive system. The rubberless artificial muscle is a pneumatic artificial muscle that uses no rubber tube. It can contract by low pressure, but it has nonlinear characteristics including hysteresis characteristics. For this study, we apply the rubberless artificial muscle to an antagonistic drive system. Then we control an antagonistic position and antagonistic force. A two degree-of-freedom (2DOF) control system that includes a mechanical equilibrium model showing the static characteristic of the rubberless artificial muscle is applied. In addition, contraction force is controlled by another 2DOF control system. From experimentally obtained result, it was confirmed that the antagonistic position is almost identical to the target position. Furthermore, antagonistic force is also controlled appropriately even if the antagonistic position is moving.

KEY WORDS

Pneumatic actuator, Artificial muscle, Antagonistic drive system, Rubberless artificial muscle

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>F</td>
<td>Force</td>
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<tr>
<td>P</td>
<td>Pressure</td>
</tr>
<tr>
<td>X</td>
<td>Length from maximum contraction</td>
</tr>
<tr>
<td>K</td>
<td>Stiffness coefficient</td>
</tr>
<tr>
<td>l</td>
<td>Length of the string of sleeve</td>
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<tr>
<td>n</td>
<td>Number of turns of the string of sleeve</td>
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<td>θ</td>
<td>Angle of the mesh of sleeve</td>
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<td>µ</td>
<td>Friction coefficient</td>
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>K_{sys}</td>
<td>Stiffness coefficient of the system</td>
</tr>
<tr>
<td>ΔF</td>
<td>Outer force</td>
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<tr>
<td>Δx</td>
<td>Displacement generated by ΔF</td>
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INTRODUCTION

In recent years, many studies have been conducted to examine the application of the pneumatic artificial muscle[1][2]. The artificial muscle is lightweight, but it is able to generate high power, and can maintain compliance characteristics necessary for the use of air pressure. Therefore, it is anticipated for application to wearable devices, robot actuators, etc. In progressing with applications of the pneumatic artificial muscle, several new pneumatic artificial muscles have been
A rubberless artificial muscle (RLAM), one such artificial muscle, uses an airbag made of inelastic material instead of a rubber tube. The one purpose of the development of this artificial muscle is to resolve the problem of aged deterioration or characteristic changes by the residual stress of rubber. Currently, research on the application of this rubberless artificial muscle to mechatronics systems is underway.

One application of the pneumatic artificial muscle to mechatronics systems is for an antagonistic position and stiffness control of an antagonistic drive system[6]. The antagonistic position control is conducted using a two degree-of-freedom (2DOF) control system including an inverse model of the static characteristic of the pneumatic artificial muscle [7], nonlinear model-based control[8], etc. In addition, the antagonistic position and stiffness of the antagonistic drive system is controlled by a mathematical model that expresses the relation of position and force of the antagonistic system including a static model of the pneumatic artificial muscle[9].

However, most pneumatic artificial muscles have nonlinear characteristics that are caused by friction; it is therefore difficult to obtain a mathematical expression with high accuracy. Especially, the rubberless artificial muscle has a large hysteresis loop in terms of extension and contraction. The mathematical model output differs from the actual response. To control the antagonistic position and stiffness of the antagonistic drive system driven by such actuators, it is necessary to compensate model errors using the feedback control of a contraction displacement and contraction force of the actuator.

Therefore, this study examines the position and force control of the antagonistic drive system using a rubberless artificial muscle including large model error. For this study, a 2DOF control system is adopted. It is effective for control of the pneumatic artificial muscle, which has nonlinear characteristics. The feedback control of force is added to the feedback control of position performed conventionally.

Based on results obtained from this experiment, we can confirm the possibility of achieving control of the position and stiffness of the antagonistic drive system using the rubberless artificial muscle.

**RUBBERLESS ARTIFICIAL MUSCLE ANTAGONISTIC DRIVE SYSTEM**

**Rubberless artificial muscle**

The rubberless artificial muscle used for this study is presented in Fig. 1.

The basic structure and drive mechanism of the rubberless artificial muscle are the same as those of the McKibben type artificial muscle.

A typical McKibben type artificial muscle consists of a sleeve made by thin polyester codes that are knitted to produce a cylindrical net, a rubber tube inserted in the sleeve that expands by compressed air, and hose bands.

![Figure 1 Rubberless artificial muscle (RLAM).](image1)

![Figure 2 Relation between inner pressure and displacement of RLAM.](image2)

\[ F = KX \] (1)

to fix these components.

When the compressed air expands the rubber tube, the sleeve is also expanded to the diameter direction. Furthermore, the sleeve contracts in an axial direction by the pantograph mechanism of the sleeve. Because the rubberless artificial muscle has few metal parts, it is lightweight, with structural softness.

The rubberless artificial muscle is constructed by an airbag made of inelastic material instead of an inner rubber tube of a McKibben type artificial muscle.

The relation between inner pressure and contraction displacement of the rubberless artificial muscle when contraction force is fixed is presented in Fig. 2. This result confirmed that the contraction displacement decreases concomitantly with increasing contraction force. In addition, the relation is nonlinear. Changes of the contraction displacement of the rubberless artificial muscle decrease concomitantly with decreasing muscle length. Furthermore, results show that it has hysteresis characteristics. These characteristics make derivation of a high accurate mathematical model and control of the rubberless artificial muscle difficult.

Figure 3 shows isometric contraction characteristics of the rubberless artificial muscle. Based on this result, when the inner pressure is constant, the contraction force and length from the maximum contraction have a linear relation, and it is shown as below:

\[ F = KX \] (1)
The stiffness coefficient $K$ shows a gradient of the result of each pressure in Figure 3. It changes according to the pressure. Figure 4 presents the relation between pressure and the stiffness coefficient. Based on this result, it can be inferred that the rubberless artificial muscle is an actuator, similar to a spring, that can change stiffness.

Where, the stiffness coefficient is rewritten as $K(P)$, the characteristic of the rubberless artificial muscle is expressed approximately as shown below:

$$F = K(P)X$$  \hspace{1cm} (2)

In this study, the antagonistic drive system driven by the rubberless artificial muscle with such characteristics is controlled.

**Antagonistic drive system**

The antagonistic drive system driven by the rubberless artificial muscle used for this study is depicted in Fig. 5. Two rubberless artificial muscles are placed on the same axis. One end of each rubberless artificial muscle is fixed to the base. The other end of each is connected through a load cell. The load cell can move along one axis by a slide guide. The place where each rubberless artificial muscle and the load cell are connected is called an antagonistic position in this system. The experimental setup of the antagonistic drive system is depicted in Fig. 6. The antagonistic position is measured using a position sensor. In addition, in this system, the antagonistic force generated by both rubberless artificial muscles is measured by the load cell. The inner pressure of each rubberless artificial muscle is changed by an electro-pneumatic regulator (SMC, ITV2030). Measurement and control are performed through Matlab/Simulink on a PC. Position control considering antagonistic force becomes possible using these measured results.

**STIFFNESS MODEL OF ANTAGONISTIC DRIVE SYSTEM**

The antagonistic drive system can control the position and force. Control of the position and force is equal to control of the stiffness corresponding to the external force added to the antagonistic position. Here, we derive a stiffness model of the antagonistic drive system when it is considered that the rubberless artificial muscle is a variable stiffness element, as described above. Based on this model, we summarize the necessity for control of the antagonistic position and antagonistic force.

Figure 7 presents a dynamic model of the antagonistic drive system. Here, the place where the extension from the amount of the maximum contraction of each rubberless artificial muscle becomes equal is called a neutral position $x_c$. Furthermore, the antagonistic force is described to be $F_A$. Displacement $\Delta x$ is generated by external force $\Delta F$ acting on the antagonistic point.
Characteristics of each rubberless artificial muscle are expressed using neutral position $x_c$ and antagonistic position $x$ as follows.

$$F_A = K_1(P_1)(x_c + x)$$  \hspace{1cm} (3)

$$F_A = K_2(P_2)(x_c - x)$$  \hspace{1cm} (4)

Here, the characteristic of each rubberless artificial muscle is changed by the outer force $\Delta F$ as follows.

$$F_A + \Delta F = K_1(P_1)(x_c + x + \Delta x)$$  \hspace{1cm} (5)

$$F_A - \Delta F = K_2(P_2)(x_c - x - \Delta x)$$  \hspace{1cm} (6)

Based on those equations, the relation between outer force $\Delta F$ and displacement $\Delta x$ is the following.

$$\Delta F = \frac{K_1(P_1) + K_2(P_2)}{2} \Delta x$$  \hspace{1cm} (7)

In this equation, the stiffness of this system $K_{sys}$ is expressed using the stiffness of each rubberless artificial muscle as shown below.

$$K_{sys} = \frac{K_1(P_1) + K_2(P_2)}{2}$$  \hspace{1cm} (8)

Here, the stiffness of this system is rewritten using the antagonistic position and antagonistic force by Eqs. (3) and (4) as the following equation.

$$K_{sys} = \frac{x_c}{(x_c + x)(x_c - x)} F_A$$  \hspace{1cm} (9)

From the derived Eq. (9), it was confirmed that the stiffness of this system is changed by the antagonistic position and antagonistic force. Figure 8 presents the result when $K_{sys}$ is set to 5 kN/m. To coincide with the stiffness of this system with a target value, it is necessary to change the antagonistic position and antagonistic force continuously.

**CONTROL SYSTEM**

For control of the rubberless artificial muscle antagonistic drive system, it is necessary to control the contraction displacement and force of each rubberless artificial muscle. Therefore, for this study, we design a control system and confirm the possibility of controlling the antagonistic position and antagonistic force of the antagonistic system.

The relation between pressure and the contraction displacement of the rubberless artificial muscle is nonlinear when the force is constant. Moreover, it has hysteresis characteristics. The delay in the response of contraction displacement control that results from these characteristics affects the antagonistic force. Therefore, suitable stiffness might be unrealizable. It is desirable that the contraction displacement of each artificial muscle reaches a desired value promptly.

For the reasons given above, in this study, a 2DOF control system is applied to each rubberless artificial muscle as shown in Fig. 9. This control system comprises two elements. One is a feed-forward element that compensates the rubberless artificial muscle linearly by a mechanical equilibrium model [10] that shows the relation between force, displacement, and pressure. The other is a feedback controller that compensates a modeling error.

Compared with a control that uses no mathematical model, it is expected that the response of contraction displacement control improves and that it can achieve a target stiffness of the antagonistic system.

The mechanical equilibrium model that is used in this control system is expressed as the following equations.
The parameters were determined based on the actual size with slight trial-and-error adjustment. The characteristics of the model are depicted in Fig. 10. For mathematical expression of the hysteresis characteristic using the mechanical equilibrium model, the parameters were determined so that the solution of the model might pass along the center of the hysteresis loop.

The antagonistic force is the parameter which affects the stiffness of the system, it is necessary for control of the contraction force of each rubberless artificial muscle. Therefore, the force control is added to the displacement control, as presented in Fig. 11. In this control system, the value of force inputted into the mechanical equilibrium model is adjusted, reflecting an error. It is expected that contraction displacement and the force of each rubberless artificial muscle is controlled with accuracy by this control system. In the next chapter, the usability of this control system is confirmed through several experiments.

\[
F = \frac{t^2}{n} \left( \frac{1}{4\pi n} \left( 3 \cos^2 \theta - 1 \right) - \mu \sin \theta \cos \theta \right) \text{P} \quad (9)
\]

\[
X = t \left( \cos \theta - \frac{1}{\sqrt{3}} \right) \quad (10)
\]

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**EXPERIMENTAL RESULT**

**Dynamic characteristics of the system**

To confirm the usability of the control system, it is important to evaluate the dynamic characteristics of the response. Therefore, first of all, we compare the step response in the case of feedback control using only the antagonistic position and feedback control using both the position and force of the antagonistic point.

Figure 12 presents the results of feedback control using only the position data. Figure 13 shows the result of feedback control using both position and force. From these results, in the case of feedback control using both the position and force of antagonistic point, the response of antagonistic position reaches the target value promptly. Moreover, the antagonistic force is mostly in agreement with the target value. In the case of feedback control using only the antagonistic position, the result of antagonistic force differs from the target value. When the target value of antagonistic force becomes a steady state, the actual response also converges on a steady state. It is considered that the cause of this difference is modeling error. Therefore, to control the artificial muscle for which it is difficult to obtain a mathematical model with high accuracy, the proposed control system is effective.
Adjustment of system stiffness

Next, an experiment was conducted in which the target value of the antagonistic position and antagonistic force are changed continuously. The target value is calculated using the stiffness model derived in a previous section. The result of feedback control using only the position data and the result of feedback control using position data and force data are presented respectively in Fig. 14 and Fig. 15. From Fig. 14, the actual force response has a constant error, although the changing tendency is the same as the target value. The cause of the tendency is a modeling error. The rubberless artificial muscle also has a hysteresis characteristic. It is difficult to cancel a modeling error by parameter adjustment. In contrast, in the case of feedback control using position data and force data, the actual response is almost identical to the target value. Therefore, a feedback control system using an antagonistic position and antagonistic force is important to realize target stiffness.

Finally, the experimentally obtained result in which the frequency of the target position is increasing is presented in Fig. 16. In this experiment, only the feedback control system using position data and force data was applied. The frequency of the target position is set to 0.2 Hz. In this result, the actual antagonistic position does not reach the target position near the peak magnitude. Furthermore, the response has a phase delay. However, the actual response of the position and force follows the target value with the small error. Therefore,
this control system is effective to realize the stiffness of the antagonistic drive system.

That result presents the possibility that this response improves considering dynamic characteristic compensation. Design of the control system including dynamic characteristic is left as a subject for future study.

**SUMMARY**

In this study, a control system of the antagonistic position and antagonistic force to realize the position and stiffness control of the antagonistic drive system using the rubberless artificial muscle is examined. In this study, a 2DOF control system is adopted. The control system includes a mechanical equilibrium model as a reference model.

The controlled performance of the 2DOF control system was confirmed experimentally using only position feedback data and the effect of addition of the feedback control of antagonistic force to this system. Results obtained from this study can be summarized as described below.

A mathematical expression of the stiffness of the antagonistic drive system using the rubberless artificial muscle is derived. This expression shows that the stiffness is determined by the position and force of the antagonistic point.

To control both the antagonistic position and antagonistic force, the antagonistic force feedback control was added to the 2DOF antagonistic position control system. Both the antagonistic position and antagonistic force were approximately equal to the target values. Therefore, this system can realize the position and stiffness control of the antagonistic drive system using the rubberless artificial muscle.

**REFERENCES**


![Sinusoidal response of 2DOF control system](image)