DEVELOPMENT OF A FLEXIBLE PNEUMATIC ACTUATOR WITH A FLEXIBLE TUBE

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ABSTRACT

Recently, virtual reality systems have been flourishing as an interactive information technology. However, current virtual reality systems are not enough to realize a force feedback system for hands, arms, legs and so on. Furthermore, due to the ageing in Japanese society and the decreasing birthrate, an increasing problem of providing nursing care for the elderly has occurred. As a result, it is necessary to develop systems to aid in nursing care. The actuators necessary for such a feedback system, as for power assisted nursing care of the elderly, need to be flexible so as not to injure the human body. The purpose of our study is to develop a flexible and lightweight actuator which can be safe enough to be mounted on the human body.

In this study, we propose a new type of flexible pneumatic actuator that can be used even if the actuator is deformed by external force. We tested two types of flexible pneumatic cylinder. One type uses rubber balls and the other type uses Y-ring type gaskets to seal the cylinder head. The elastic pneumatic cylinder consists of a flexible tube as a cylinder and an elastic cylinder head consisting of rubber balls and gaskets. We investigated the relation between generated force and supply pressure for the bent cylinder tube. And we proposed the analytical model of the actuator and identified system parameters of the actuator in order to design it. As a result, we confirmed that the tested flexible pneumatic cylinder was very useful to be applied as an actuator that can be set on the human body with advantages of flexibility, lightweight and large ratio of the generated force to weight.
INTRODUCTION

Recently, the ageing in Japan and the decreasing birthrate have caused an increasing problem of providing nursing care for the elderly. As a result, it is necessary to develop systems mounted on the human body to support in nursing care task. Furthermore, taking notice of recent information technology, virtual reality systems have been flourishing as an interactive information technology. Recent virtual reality systems that feed back to human senses have been realized as visual and acoustic feedback. However, they are not enough to realize a force feedback system for hands, arms, legs and so on. The actuators necessary for such a feedback system, as for power assisted nursing care of the elderly [1], need to be a lightweight and flexible so as not to injure the body. The purpose of our study is to develop a flexible and lightweight actuator which can be safe enough to be mounted on the human body.

In this study, we propose a new type of flexible pneumatic actuator [2] that can be used even if the actuator is deformed by external force, and tested two types of flexible pneumatic cylinder. One type uses rubber balls and the other type uses Y-ring type gaskets to seal the cylinder head. And we investigated the relation between generated force and supply pressure for the cylinder head locating on several points of the curved cylinder tube. Furthermore we propose an analytical model of the tested flexible actuator and identify the system parameters in order to design the actuator and control system. Finally, we confirm the validity of the analytical model and identified system parameters by comparing the calculated results with experimental results.

CONSTRUCTION AND OPERATING PRINCIPLE

CONSTRUCTION OF ACTUATOR

Figure 1 shows the construction of the actuator. The tested actuator is a kind of elastic pneumatic cylinder which has flexible characteristics. In order to realize flexibility, the actuator consists of a flexible tube as a cylinder, a nylon string as a rod, one-touch joint type tube connector and an elastic cylinder head (piston) consisting of rubber balls and gaskets. Using the one-touch joint type tube connector, it is easy to connect the tube and adjust the stroke of the actuator. By using the flexible tube as a cylinder, the cylinder expands toward the radius direction of the tube according to the input pneumatic pressure. Therefore, the cylinder head needs the device for sealing between the cylinder head and tube inner wall. In our research, we tested two types of flexible cylinder head. One type uses rubber balls and the other type uses Y-ring type gaskets to seal the cylinder head.

Figure 2(a) shows the tested cylinder head using rubber balls. We call it a “ball type cylinder”. The ball type cylinder has three rubber balls whose diameters are 5.0 mm and centers are penetrated by a nylon string (whose outer diameter is 1.3 mm). On both sides of the series of balls, there are two stoppers connected
with a nylon string. The balls can slide along the nylon string between the two stoppers. Figure 2(b) shows
the other type of cylinder head. We call it a **hybrid type cylinder**. The cylinder head consists of two
rubber balls, two Y-ring type gaskets which have outer diameters of 8.0 mm and inner diameter of 5.0 mm,
four sealing washers and an O-ring. The Y-ring type gaskets are set on the circumferential faces of the
rubber balls. Each pair of ball and gasket is placed between two washers. An O-ring is placed between
both pairs. They are penetrated by a nylon string and nipped with two stoppers connected with a nylon
string. The actuator is very lightweight compared with any conventional pneumatic cylinders. The whole
mass of each type of actuator with a stroke of 1 m is less than 0.1 kg

**OPERATING PRINCIPLE OF ACTUATOR**

Figure 3(a) and (b) show the operating principle for sealing between the cylinder head and the tube. The
operating principle of the ball type cylinder, as shown in Fig.3(a), is as follows: When a supply pressure is
applied to one side of the cylinder, the elastic cylinder tube expands and the inner diameter of the tube
becomes larger. At that time, the balls slide and are pushed toward the opposite side of the tube. The balls
expand to the radial direction and this keeps a seal between the cylinder head and tube.

The operating principle of the hybrid type cylinder, as shown in Fig.3(b), is similar to the ball type. In the
hybrid type, when a supply pressure is applied, two pairs of balls and gaskets slide and compress toward an
axial direction of tube. The balls and Y-type gaskets expand to the radial direction and keep a seal between
the cylinder head and tube. Then the actuator generates force according to the supply pressure.
ANALYTICAL MODEL OF ACTUATOR

NOMENCLATURES

A : effective sectional area of cylinder tube or inlet [m²]
C : damping coefficient of pneumatic cylinder [Ns/m]
d : inner diameter of cylinder tube or outer diameter of cylinder head [m]
D : outer diameter of cylinder tube [m]
F : force generated by pressure or friction [N]
k : equivalent spring constant of cylinder head and tube [N/m]
m : equivalent mass of cylinder head and rod [kg]
P : absolute pressure of input pressure [Pa]
Q : mass flow rate [kg/s]
R : gas constant [J/(kg · K)]
T : absolute temperature [K]
V : chamber volume [m³]
x : displacement of rod or cylinder head [m]
y : displacement in radius direction of tube [m]
ρ : density of air [kg/m³]
μ : coefficient of friction
κ : specific heat ratio of air (=1.4)

In symbols with a subscript, the first subscript (a, H, i, R or T) indicates the element, i.e., atmosphere (outside of cylinder), cylinder head, inner chamber of cylinder or cylinder tube. The last subscript 0 indicates the initial value of each quantity.

ANALYTICAL MODEL OF ACTUATOR

In order to design the flexible pneumatic actuator and control system using the actuator, they need an analytical model of the actuator. Figure 4 shows the analytical model of the tested flexible actuator. The proposed model factors in the fact that the inner and outer bore of the cylinder or the cylinder head increases according to the input pressure.

Assuming the change of state of gas in the cylinder chamber is adiabatic, the following expression is derived from the law of energy conservation.

\[
\frac{dP_i}{dt} = \frac{\kappa R T_i}{V_i} Q_i - \frac{\kappa P_i}{V_i} \frac{dV_i}{dt}
\]  

(1)

Mass flow rate in the inlet can be described by

\[
Q_i = c_d A_S P_S \sqrt{\frac{2}{RT}} f \left( \frac{P_i}{P_S} \right)
\]  

(2)

The function f(z) in equation (2) is given by
Equations of motion for cylinder head connected with a nylon rod is given as follows:

\[ m_i \frac{d^2 x}{dt^2} + c_i \frac{dx}{dt} = A_i (P_i - P_a) - F_{hf} - F_L \]  

(4)

where \( F_{hf} \) represents the frictional force between the cylinder head and tube, \( F_L \) is the force acted on the cylinder rod. The frictional force \( F_{hf} \) is expressed by using the force \( F_H \) which the cylinder head pushes the inner surface of the tube, and is given as follows:

\[ F_{hf} = \mu F_H \]  

(5)

where \( \mu \) means the coefficient of friction between the cylinder head and tube.

Assuming the equivalent spring constant of the cylinder head is smaller than the spring constant of tube: the elastic cylinder is softer than the cylinder tube, initial force (in the condition of no input pressure) which pushes on the inner wall of the tube is given by

\[ F_{H0} = k_H (d_{H0} - d_{T0}) \]  

(6)

where, \( d_{H0} \) and \( d_{T0} \) show initial outer diameter or cylinder head and initial inner diameter of the cylinder tube which does not expand with input pressure, respectively. Assuming that the input pressure applied to the cylinder head and tube in the condition that the cylinder head does not exist in the cylinder tube, the inner diameter of cylinder tube \( d_T \) and the outer diameter of cylinder head \( d_H \) are given as follows:

\[ d_T = d_{T0} + \frac{A_T}{k_T} (P_i - P_a) \]  

(7)

\[ d_H = d_{H0} + \frac{A_H}{k_H} (P_i - P_a) \]  

(8)

In order to seal, it must satisfy the following inequality \( d_H > d_T \). Assuming the following relation \( k_T >> k_H \) is satisfied, the force \( F_H \) in which the cylinder head pushes on the inner wall of the cylinder tube is given approximately as follows:

\[ F_H = k_H (d_H - d_T) \]  

(9)

From the relation \( k_H/k_T = 0 \), the force \( F_H \) is approximated by

\[ F_H \approx k_H (d_{H0} - d_{T0}) + A_H (P_i - P_a) \approx F_{H0} + A_H (P_i - P_a) \]  

(10)

The effective sectional area of the cylinder head is depended on the inner diameter of the tube, and is given as follows:

\[ A_i = \frac{\pi}{4} \frac{d_T^2 - d_R^2}{4} = \frac{\pi}{4} \left( d_{T0}^2 + \frac{A_T}{k_T} (P_i - P_a) \right)^2 - \frac{\pi}{4} d_R^2 \]  

(11)

We can predict the static and dynamic characteristics of the tested flexible pneumatic actuator by solving equation (1) to (11).
EXPERIMENTAL EQUIPMENT

![Experimental Equipment Diagram]

We investigate the relation between applied pressure and generated force of the tested flexible pneumatic actuator. Figure 5 shows the experimental equipment for measuring the generated force according to input pressure. The equipment consists of the tested actuator and a digital force gauge (with measuring range of ± 50N and measuring resolution of 0.1 N) which were fixed on the table.

In the experiment, the cylinder rod (nylon string) is connected to the digital force gauge. We investigated the generated force according to input pressure (from 0 to 450 kPa) in two conditions which the stroke shape of the flexible actuator is kept straight or bent. In order to investigate the leakage of air, we measured the pressure in the cylinder chamber and supply pressure by using two pressure sensors. In measuring of the straight tube, the cylinder head (piston) was located at 150 mm distance from the tube connector. In the case of the bent tube, the radius of curvature of the cylinder stroke is 100 mm. We measured the generated force where the cylinder head was located at \( \theta \) (= 45, 90 and 135) degrees from the center of the circle of curvature. For the material of the cylinder tube, we used soft and hard types of polyurethane tube (SMC Co.Ltd. TU1208 or TU0805 and TUS1208).

In addition, we investigated the relation between the inner diameter of the cylinder tube and input pressure by measuring the outer diameter of the tube according to the input pressure by use of no contact type digital microscope (KYENCE Co. Ltd.: VH-6300).

EXPERIMENTAL RESULTS

RELATION BETWEEN INPUT PRESSURE AND GENERATED FORCE

Figure 6 (a), (b) and (c) show relations between input pressure and generated force of the tested actuators. Figure 6(a) shows experimental results by using the ball type cylinder head as a piston and hard type polyurethane tube as a flexible cylinder. Figure 6(b) and (c) show the results of the hybrid type cylinder, using the soft and hard type polyurethane tubes as cylinders, respectively. In these figure, symbols \( \diamond \), \( \bigcirc \), \( \triangle \) and \( \square \) show the measuring data in the case that the cylinder tube was kept straight and the cylinder head was located on the point of 45, 90 and 135 degrees from the center in the curved cylinder tube as shown in Fig.5. Broken lines show the theoretical value calculated by the following equation, assuming that there is no friction between the cylinder head and tube.

\[
F = \frac{\pi}{4} \left( d_1^2 - d_2^2 \right) \left( P_i - P_a \right)
\]  

(12)
where, \( d_1 \) shows an inner diameter of the cylinder tube. \( d_2 \) shows an outer diameter of the rod. \( P_i \) and \( P_a \) show input pressure and atmospheric pressure, respectively. From Fig. 6, we can find that relations between input pressure and generated force of the cylinder are almost linear even if the cylinder tube is bent. In the results using a straight cylinder tube, the generated force in the case using both types of cylinder becomes maximum. It can be found that the generated force decreases as the angle \( \theta \) in the bent cylinder tube becomes larger. We thought that it was caused by the nylon wire (cylinder rod) contacting the inner wall of the cylinder tube; increasing contact area according to angle \( \theta \), friction becomes larger. It can be found that output force generated by using the hybrid type cylinder is about 20 N in spite of the whole weight of less than 0.1 kg with the stroke of 1 m. We can recognize that a ratio of generated force to weight of the tested cylinder is larger than usual pneumatic cylinders in spite of a long stroke of more than 1 m.

**INFLUENCE OF CYLINDER HEAD SHAPE**

Comparing characteristics of generated force using the ball (as shown in Fig. 6(a)) and hybrid type cylinders (as shown in Fig. 6(C)), we can see that the hybrid type cylinder is superior to the ball type from the point of view of larger generated force. Because the difference of the generated force between the hybrid type cylinder tube kept straight and curved is smaller than the result using the ball type cylinder. We think that the ball type cylinder is more affected by friction in a curved tube, because the ball type cylinder head makes greater contact force with the cylinder tube compared with the hybrid type.

In order to compare the sealing performance of both types, Fig. 7 shows relations between supply pressure and inside pressure of both types of cylinder. Each symbol shows the different cylinder heads and cylinder tubes. From Fig. 7, we can see that the differ-
ence between input and inside pressure is very small; less than 3 kPa with an inside pressure of 450 kPa. In additional experiment we confirmed that the sealing performance of the hybrid type was superior to the ball type, because the ball type cylinder has a little leakage between the cylinder head and tube.

IDENTIFICATION OF SYSTEM PARAMETERS

In order to calculate the maximum output force of the proposed actuator, we identified the system parameters of the actuator by comparing theoretical results with experimental ones. In identification, we use the following conditions:

1) Ignoring the data when generated force $F_L$ is zero, because it includes the static frictional force.
2) Using the measured data when the cylinder tube is kept straight, because there exists the frictional force between the nylon rod and cylinder tube in the case of curved cylinder tube.

As identified parameters, we choose the parameters $\frac{A_T}{k_T}$, $\mu A_H$, $\mu F_{H0}$ and $\mu k$ which are necessary to calculate the generated force.

When we consider the steady state of the motion in Equation (4), static generated force is given by

$$F_L(\Delta P) = \frac{\pi}{4} \left( \frac{A_T}{k_T} \right)^2 \Delta P^3 + \frac{\pi}{2} \frac{A_T}{k_T} d_{T0} \Delta P^2 + \frac{\pi}{4} \left( \frac{d_{T0}^2}{d_r^2} - \frac{d_r^2}{d_T^2} \right) \Delta P - \mu F_{H0}$$  \hspace{1cm} (13)

where $\Delta P$ shows the differential pressure $P_i - P_a$.

Assuming that a sectional area of the tube material after and before input is constant, an inner diameter of the tube $d_r$ is given as follows:

$$d_r = \sqrt{D_r^2 - d_{T0}^2 + d_{T0}^2}$$  \hspace{1cm} (14)

The inner diameter of the tube is related to input pressure, and is approximated by the following equation.

$$d_r(\Delta P) = d_{T0} + \frac{A_T}{k_T} \Delta P$$  \hspace{1cm} (15)

The relation between the parameter $F_{H0}$ and $\mu k_H$ is given by following relation.

$$\mu k_H = \frac{\mu F_{H0}}{d_{H0} - d_{T0}}$$  \hspace{1cm} (16)

The parameter $A_T/k_T$ in Equation (13) is estimated by measuring an outer diameter of the tube according to input pressure. Fig. 8 shows the relation between input pressure and change of inner diameter of tube. In Fig. 8, symbols shows averaged values measured by using various tubes, vertical lines show scatter of data. Solid lines show the calculated values by using Equation (16) and identified parameter $A_T/k_T$. We can see that relation between input pressure and inner diameter of
tube is almost linear. It can be found that calculated values agree with experimental results. We confirm the validity of the model and identified parameters.

In order to identify the system parameter $A_H$ and $F_{H0}$, we compare the calculated value by Equation (13) with the experimental results of generated force. Figure 9 (a), (b) and (c) show the comparison between theoretical and experimental results of generated force. Figure 9 (a) and (b) show the results by using the hybrid type cylinder. Figure 9 (c) shows the results by using ball type cylinder. Each figure shows generated force in ordinate and input pressure in abscissa. In these figures, symbol $\circ$, $\square$ and $\diamond$ show the experimental results and solid line shows the calculated results by using equation (13) and identified parameter $A_T / k_T$, $A_H$ and $F_{H0}$.

From Fig.9, it can be found that calculated results agree well with experimental results of generated force in both of hybrid and ball type cylinders. We can confirm the validity of model and identified parameters. As the results, we can get the identified parameters as shown in Table 1. By using these parameters and analytical model of the actuator, it is possible to calculate system parameter such as an inner diameter of tube in order to get the performance of the actuator such as a maximum generated force.

**TABLE 1 SYSTEM PARAMETERS**

<table>
<thead>
<tr>
<th>TUBE</th>
<th>$A_T / k_T$ [m$^3$/N]</th>
<th>$\mu A_H$ [m$^2$]</th>
<th>$\mu F_{H0}$ [N]</th>
<th>$\mu k_H$ [N/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>POLYURETHANE (d$_T$=8mm)</td>
<td>$6.96 \times 10^{-10}$</td>
<td>$7.24 \times 10^{-6}$</td>
<td>1.27</td>
<td>$3.26 \times 10^3$</td>
</tr>
<tr>
<td>SOFT POLYURETHANE (d$_T$=8mm)</td>
<td>$8.86 \times 10^{-10}$</td>
<td>$5.54 \times 10^{-6}$</td>
<td>1.02</td>
<td>$2.16 \times 10^3$</td>
</tr>
<tr>
<td>POLYURETHANE (d$_T$=5mm)</td>
<td>$5.74 \times 10^{-10}$</td>
<td>$3.03 \times 10^{-6}$</td>
<td>1.41</td>
<td>$3.07 \times 10^4$</td>
</tr>
</tbody>
</table>

**FEATURE AND APPLICATION**

The tested flexible pneumatic actuator is a kind of new actuator. This has some advantages compared with a usual pneumatic cylinder type actuator. The actuator constructed is more compact, and has lighter weight and flexible. Construction of the actuator is very simple. It is possible to deform cylinder tube for working the actuator because it is more endurable for impact and deformation. By using one touch tube connector, we can freely adjust and easily change the stroke of cylinder after even if we bought the cylinder on market. By winding the cylinder tube like a coil, we can realize the long stroke in a narrow work space.
In present situation, it has a little problems such as a pushing operation and a little leakage at the end of cylinder tube where a nylon rod is sealed.

We consider the an application of the actuator, as follows; devices for assisting to human power, supporting devices for nursing care task, medical devices, flexible actuators for usual robots, devices by using in area of internet robotics and a force feedback system such as virtual reality system.

**CONCLUSIONS**

This study aiming at the development of the flexible and lightweight pneumatic actuator which can be safe enough to be attached to human body can be summarize as follows:
1) We proposed and tested two types of flexible pneumatic cylinder which uses ball type cylinder head or hybrid type cylinder head consisted of rubber ball and gasket. We investigated the relation between input pressure and generated force in a tested flexible cylinder. As the results, it can be found that there is a linear relationship between input pressure and generated force. Furthermore we can confirm that the tested cylinder can work in the condition of curved cylinder tube.
2) It can be found that a difference between supply and internal pressure in the cylinder is less than 3 kPa when the input pressure of 450 kPa is applied. We confirm that the performance of sealing of tested cylinder is relatively good.
3) In order to design and design a control system by using the actuator, we proposed the analytical model of a flexible pneumatic cylinder and identified system parameters of the cylinder for calculating the generated force. By comparing the experimental and calculated results, we confirm the validity of the proposed model and identified system parameters.

We can expect that the flexible cylinder is useful to apply various field such as assisting for nursing care task, medical equipments, human-friendly robots and so on.

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**REFERENCES**