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Application of Passive Dynamic Control to Pneumatic Cylinders

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Abstract—**The passive dynamic control ("PDC") is a new mechanical system control method using variable passive elements with less energy and more safety. In the study described in this paper, the PDC is applied to a pneumatic cylinder for positioning control. When an object is stopped in the intermediate position by a pneumatic control and an electromagnetic friction brake, the unbalance force is cut to zero and the balanced state is achieved. Thus, high-rigidity positioning is achieved and the object can be moved to the next position. In this paper, the authors also propose a method of improving the internal pressure control precision for the cylinder.**

I. INTRODUCTION

The pneumatic control system [1] is playing an important role in machine tools, transfer lines, robot drives, etc., owing to its advantages, such as low cost installation, high output-weight ratio and faster drive compared with other drive systems. In addition, since it can operate softly and is clean with no oil leak unlike hydraulic counterparts, the pneumatic control system is expected to be applied to human-contacting machines, such as nursing instruments and service robots. However, it is considered difficult for the pneumatic system to achieve high-precision positioning due to its nonlinear elements, such as low rigidity and delay in pressure response by air compressibility, piston-cylinder sliding friction and characteristic fluctuation witnessed in plant caused by air temperature variation. Since these nonlinear elements degrade the control performance, it is difficult in principle to stop and hold the piston in the intermediate position with high rigidity. To solve these problems, some approaches have been considered [2]. For example, Pai et al. [3] designed a new pneumatic table so that the velocity compensator could overcome its stick-slip friction and thereby realized ultra-precision pneumatic positioning. Pandian et al. [4] considered the designs of observers for cylindrical actuators to evaluate the variation in the internal pressure of the cylinder (by using the measured position and velocity signals). However, neither of the new pneumatic table nor the observers had high rigidity against disturbance. Saito et al. [5] proposed a method of holding high rigidity against disturbance by installing a friction brake in the pneumatic cylinder.

Generally, in machine safety (ISO12100) [6], priority is given to inherently safe design. The authors [7] proposed a new mechanical system control method based on inherently safe design by using the passive control. This control method, which effectively used passive elements with variable properties, was named "passive dynamic control (PDC)." The authors demonstrated the effectiveness of the PDC through positioning experiments by using a spring balancer and a magneto-rheological fluid ("MR") brake. In addition, the authors [8] proposed a new rescue robot system equipped with a functionalized spring balancer as a weight reducer.

This paper describes a method of applying the PDC to the positioning of the pneumatic cylinder. The positioning with high rigidity and good energy saving can be realized by applying the PDC. In Section II, the basic principle of the PDC is explained. In Section III, the control method when the PDC is applied to the pneumatic cylinder is shown, and a method of fine-adjusting the internal pressure of the cylinder is proposed. In Section IV, the experimental results are shown, and the effectiveness of the PDC is examined.

II. BASIC PRINCIPLE OF THE PASSIVE DYNAMIC CONTROL

The mechanical positioning of the servo system can be considered in two different controls: one to generate the force for moving the control object in the direction toward the target position, and the other to achieve a balance of the forces which affect the control object by canceling each other in the other directions. The former is called "moving operation," and the latter is called "balancing operation." For such mechanical system, the authors [7] proposed the passive dynamic control ("PDC") using a passive element with variable physical properties. One system configuration of the PDC is shown in Fig. 1. In the PDC, by making efficient use of both the moving operation and the balancing operation, the energy-saving, high-safety control can be realized.

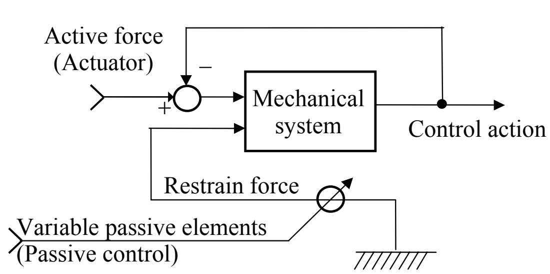

Fig.1 A system configuration of the PDC.

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Here, the basic principle of the PDC is explained as to the two different operations, i.e., the balancing operation and the moving operation.

A. Balancing operation

In the PDC, the control for achieving the balance of the forces by canceling the forces is gained by using a friction brake ("brake") and a device for achieving the balance of the forces ("balancer"). First, the control object is held by using the brake. Then, the effect of external force can be cancelled passively with no delay according to the principle of action and reaction. This action is called "hold."

However, in this state, since sudden action will occur dangerously upon the release of the hold, the hold can not be released, and it can not be moved to the next target position. Then, detecting the force applied to the brake, a balance is taken using the balancer in order to make the force 0. As an approach, the force applied to the brake is considered into two different parts, "ripple force" fluctuating the force applied to the brake minutely, and "unbalance force" denying the ripple force, as shown in Fig.2. Here, when the unbalance force is made balanced by a balancer (as shown in Fig. 2 from the solid-line state to the dotted-line state) in the hold state, the force applied to the brake can be reduced to only a small ripple force, and thereby, even if the hold state is released, there will be no occurrence of sudden action. Since the failure is not permitted in this operation, the passive element is used. Also, if the small ripple force is less than the static friction force (shaded part in Fig. 2), there will be no occurrence of action even if the hold is release, so that the static friction may suppress fluctuating force. The balance of this state is called "inherently stable balance."

B. Moving operation

In the PDC, the unbalance force is used for moving operation. After finishing the balancing operation, the permissible unbalance force (operation force) is generated in the hold state in the purpose direction (unbalance generation). The force applied to the brake is detected and, when the direction of the force coincides with the purpose direction and the size of the force is within the permissible range, the hold state is released. Upon the release of the hold state, the control object moves in the purpose direction. When the normal unbalance force cannot be confirmed, the hold state remains unreleased. Also, to ensure the safety, it may be so arranged that the change to the unbalance force after the release of the hold state should not be permitted. After accomplishing the objective, the object is stopped by the hold.

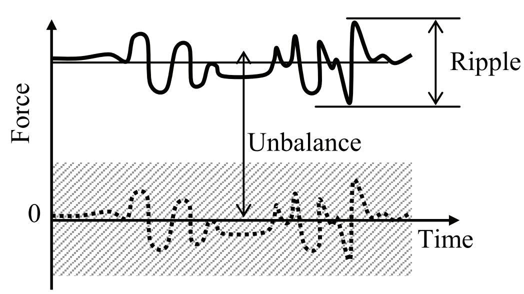


Fig. 2. Unbalance and ripple.

C. Advantages of the PDC

The PDC has advantages as follows:

a) *Safety*: The control process is divided into four steps, and each step is carried out only after confirming the conditions for safety. The dangerous runaway caused by the instability of the control system is not generated because balancing operation and unbalance generation are executed under the hold.

b) *Energy Saving*: Since the control recognizes the balanced state as the basic state, the energy required for the moving operation, which is used for the unbalance generation, is small. Also, since the balancing operation is executed by the hold, the energy required for the disturbance suppression is negligible.

c) *Stability*: Conventional stability criterion is not required since the moving operation and the balancing operation are carried out independently. Since the balancing operation is executed by the hold, the effect of disturbance or ripple does not appear as a displacement in the output as long as it remains within the permissible range. Since the forces are balanced after the hold, there is no possibility of runaway (i.e., divergence), even if the hold state is released.

d) *Adaptability*: When the force applied to the control object exceeds the permissible range, since the displacement is caused, the reactive force surpassing the hold force is not generated, even if a human contacts the object by mistake. This hold force is variable.

III. Positioning of the Pneumatic Cylinder

The pneumatic cylinder control system to be applied to the PDC is shown in Fig. 3. This system is equipped with an electromagnetic friction brake and a friction plate in pneumatic cylinder to raise the stop and hold accuracy. To add, a load cell is installed to detect the force being applied to the friction plate while it remains stopped by the brake. The rod position is measured with a laser displacement gauge.

A. Pneumatic controller

This section describes the pressure control method for the pneumatic cylinder. Fig. 3 shows the state in which all valves are OFF and the pressure is retained.

I) The pressure of chamber A is raised, and the pressure of chamber B is lowered:

When the valves A1 and B2 are turned OFF and the valves A2 and B1 are turned ON, the chamber A intakes the air and the pressure is raised, and the chamber B exhausts the air and the pressure is lowered.

II) The pressure of chamber A is lowered, and the pressure of chamber B is raised:

The valves A1 and B2 are turned ON and the valves A2 and B1 are turned OFF.

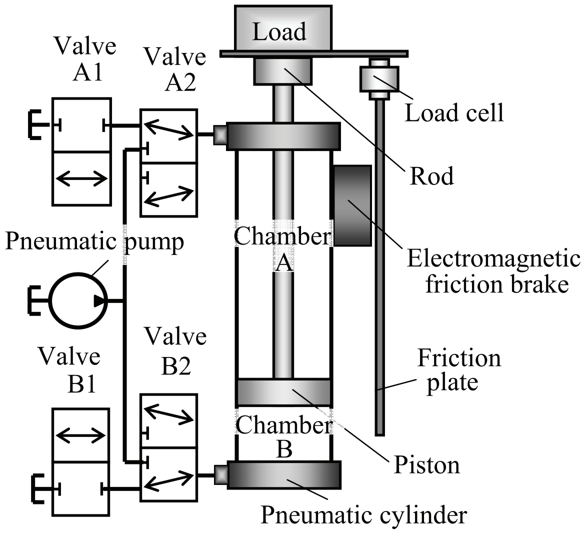


Fig. 3. Pneumatic cylinder.

B. Balance servo by the PDC

The pneumatic cylinder is problematic not only in that the positioning control is difficult to perform but also in that the velocity-control performance to zero the velocity (i.e., stop) is much lower than that of the other actuators. Also, when the control is performed to take a balance of the forces concurrently with the control of the stop, acceleration is caused, resulting in no attenuation of oscillation and failure in the stop of the control object. For this purpose, not only the control object should be decelerated, but also the balance of the forces should be taken after the precise stop that does not permit any action once the cylinder stops even if the external force below a specific threshold works is realized.

The positioning process for the pneumatic cylinder by using the PDC is shown in Fig.4 in the similar expression of the conventional linear control is shown in Fig. 4. Firstly, the control object is moved toward x_p as shown in (a). Secondly, when the control object reaches x_p, the electromagnetic friction brake is applied as shown in (b), and the braking action starts. Here, when the positioning has been achieved, the extremely stable velocity control $v(t)=0$ is performed. When $v(t)=0$ is achieved, the static friction is switched to the kinematic friction, and the compulsory balance condition is obtained only by the electromagnetic friction brake. Thirdly, after $v(t)=0$ is confirmed, the control for the balance of the forces is performed when the electromagnetic friction brake is working as shown in (c), and the force charged on the electromagnetic friction brake is made to be 0, where f_Σ is the total sum of force charged on the control object.

C. Control method

1) Basic control

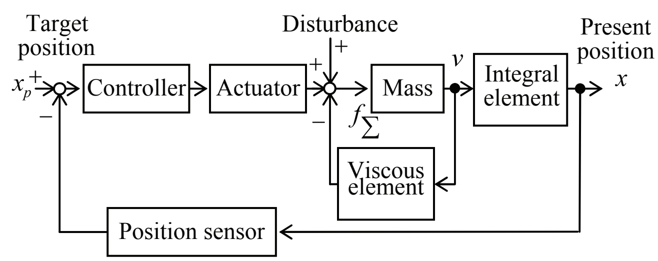
The flowchart of the basic control method is shown specifically in Fig. 5, where $x(t)$ is the present position, x_p is the target position, $F(t)$ is the force applied to the brake, which is detected by the load cell, F_p is the command value of the unbalance force, and $v(t)$ is the velocity of the rod.

i) When the target position x_p is given, the air pressure is adjusted in the hold state by the brake, and F_p in the target direction is generated.
ii) When the unbalance force $F(t)$, which is detected by the load cell, reaches F_p, the break is released.
iii) The rod moves in the target direction.
iv) When the rod reaches the target position ($x(t)=x_p$), the brake is applied to stop the rod.
v) When the rod stops ($v(t)=0$), the air pressure is adjusted in the brake-applied state, and $F(t)$ is approximated to 0.
vi) If the unbalance force is smaller than the static friction force, the brake can be released.

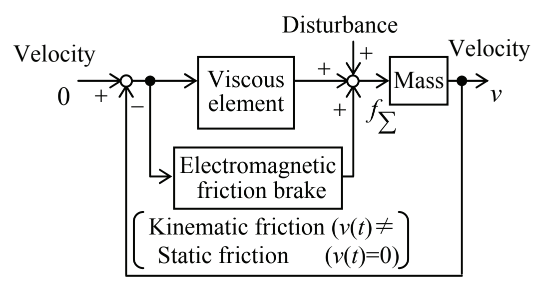
Incidentally, the information of the position used in this control is as to only whether the rod is in this side of the target position or not. The information of the deviation (i.e., the difference between the target position and the present position) is not used. In the basic control, the steady state deviation occurs inevitably by the effect of the inertial force. However, it is possible to improve the control performance.

2) Hold control

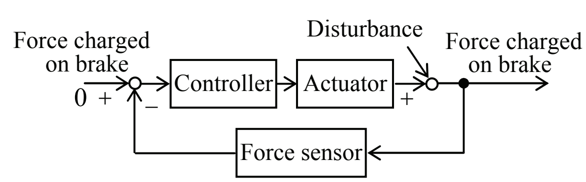
Next, the performance is improved by the brake control (i.e., hold). To eliminate this steady-state deviation, the hold start point ("HSP") is set immediately before the target position by using the information of the deviation, and when the control object reaches the HSP, the brake is applied to stop the control object.



(a) Position control (Movement to the target position).



(b) Velocity 0 control
(After reaching the target position).



(c) Balance control of the force (After stop).

Fig. 4 Control of the positioning.

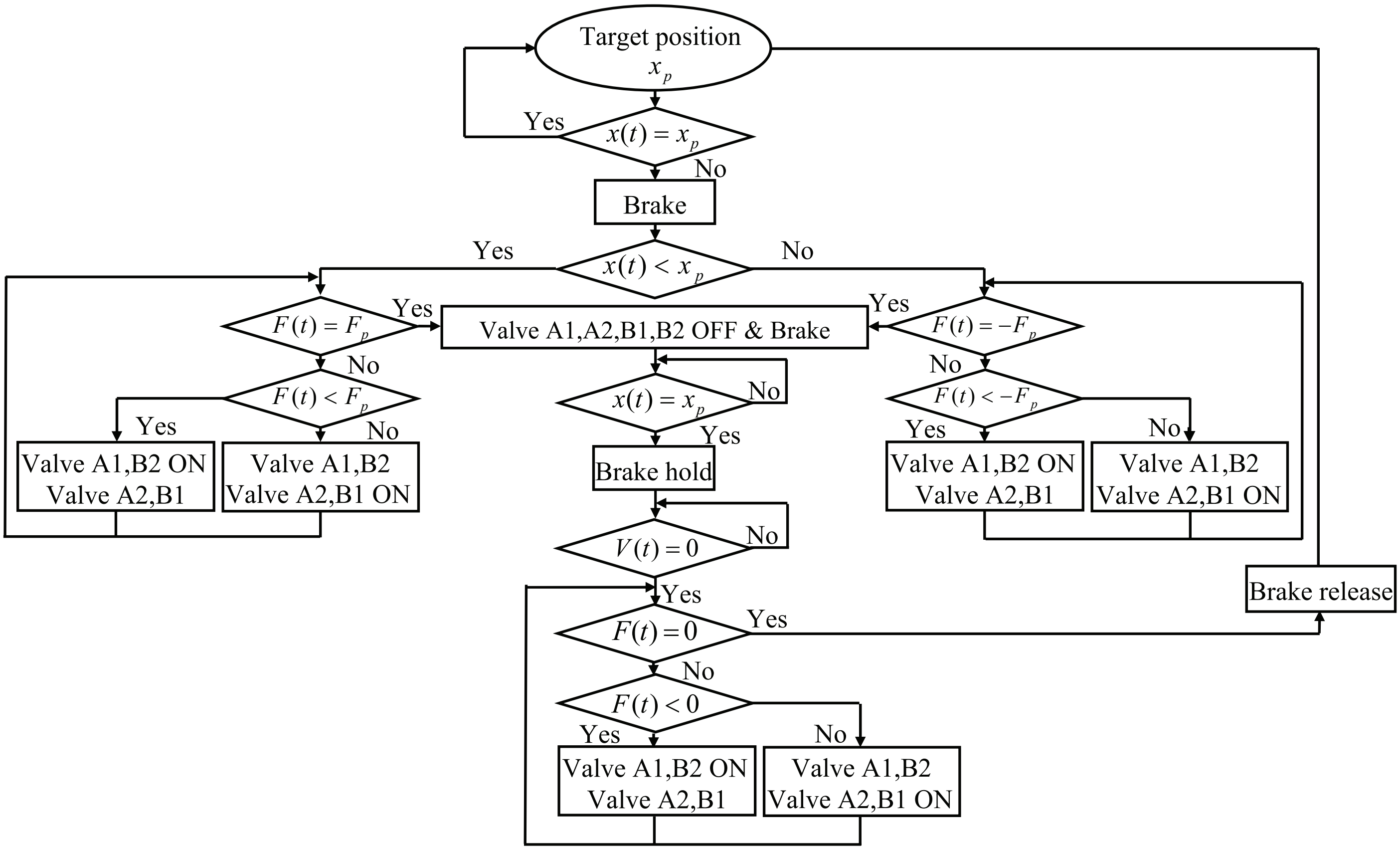


Fig. 5. Flowchart of the basic PDC.

3) Air pressure adjustment control

In the balancing operation, the smaller the friction of the slide part becomes, the higher the precision of the pressure adjustment function is required. However, a problem is that, in general, the pressure control valve is expensive. In this study, the method of fine-adjusting the internal air pressure of the cylinder is introduced. A system using two tanks is shown in Fig. 6. According to this figure, all valves are turned OFF, the valve A1 is on the exhaust side and the valve B1 is on the intake side. A case where the pressure of the chamber A of the cylinder is raised, and, at the same time, the pressure of the chamber B is lowered is supposed. While the brake is being applied, the valve A1 is switched to the intake side and the valve B1 is switched to the exhaust side, and the following steps (1) and (2) are repeated.

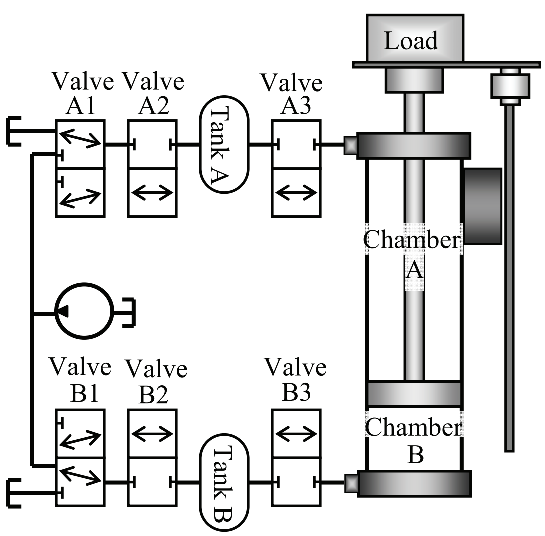


Fig. 6. Fine-adjustment of air pressure.

(1) Open the valve A2 to take the air into the tank A, and at the same time, open the valve B2 to take the air out of the tank B. When the pressures of both tanks A and B become static, close the valves A2 and B2.

(2) Open the valves A3 and B3 to raise the pressure of the chamber A and lower the pressure of the chamber B. When the pressures of both chambers A and B become static, close the valves A3 and B3.

By taking these steps, the pressures of both chambers A and B can be fine-adjusted.

Now, the change in the pressure as a result of the above steps is considered. Since the pressure adjustment is performed with the piston held by the brake, the volume of the cylinder remains unchanged. When the volume V_a of the chamber A is sufficiently small for the volume V_{ta} of the tank A, the temperature change can be neglected. Therefore, the following equation can be established before and after the above step (2):

$$p_a V_a + p_{ta} V_{ta} = p_a{}' \left(V_a + V_{ta} \right)$$

where p_a is the pressure of the chamber A, p_{ta} is the pressure of the tank A, and $p_a{}'$ is the pressure after the pressure change.

The pressure of the chamber A p_i after repeating the steps (1) and (2) for i times can be expressed by the following equations:

$$p_i = \left(1 - \alpha^i\right) p_{ta} + \alpha^i p_0$$

$$\alpha = \frac{V_a}{V_a + V_{ta}}$$

where p_0 is the pressure of the first internal pressure of the cylinder. Since it can be controlled by using the tanks so that p_i can come close to p_{ta} gradually, the internal pressure of the cylinder can be fine-adjusted.

IV. Experiments

In these experiments, a cylinder of 200 mm in stroke and ϕ40mm in diameter was used. As a result of measurement, it was confirmed that the static friction of the sliding part between the piston and the cylinder was 10N, the holding force of the brake was 70N in experiment 1 for comparison, and it was 30N in other experiments. The supply pressure was 0.2MPa.

A. Experimental methods

Experiment 1 : Using the system shown in Fig. 3, comparison was made between a case where the brake was used and a case where the brake was not used. The experiment was also conducted by setting the HSP. No load was applied and the target position was shifted from 0 mm to 150 mm.

Experiment 2 : Using the system shown in Fig. 6, the air pressure was fine-adjusted. No load was applied and the target position was shifted from 0 mm to 150 mm.

Experiment 3 : Using the system shown in Fig. 6, no load was applied, and the target position was shifted up and down continuously from 0 mm to 150 mm and to 50 mm.

Experiment 4 : In the same condition of the experiment 3, the load of 15 kg was applied.

B. Experimental results

Experiment 1 : The experimental results are shown in Fig. 7. When the brake was not used, oscillation was caused to the displacement due to air compressibility. When the brake was used, such oscillation was not caused but stead-state deviation was caused in the basic control. When the HSP was set as a countermeasure, the stead-state deviation was not caused and the control object was stopped in the target position with the precision of ±1mm. Here, the HSP was obtained experimentally.

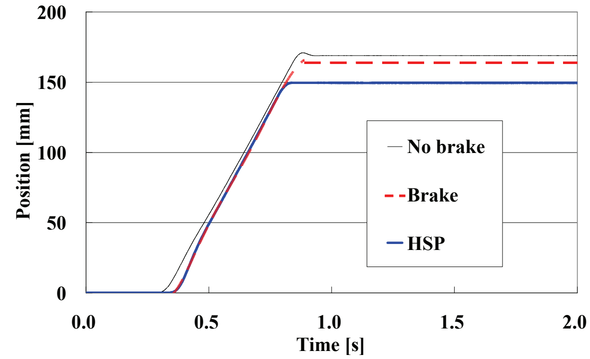
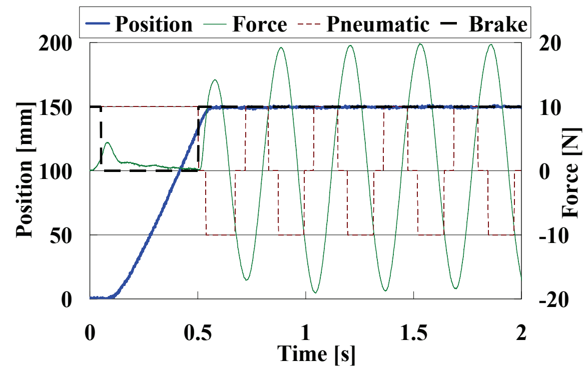
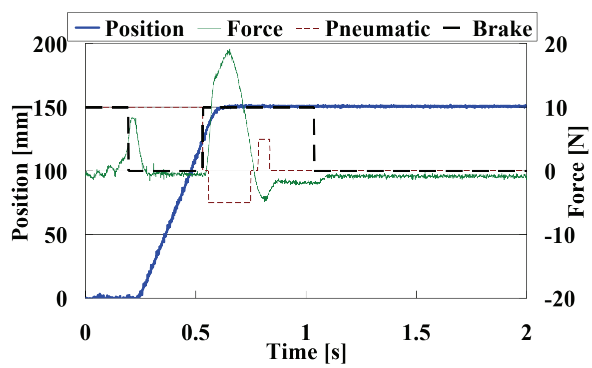


Fig.7 Experiment 1.



(a)



(b)

Fig. 8. Experiment 2.

Experiment 2 : Using the system shown in Fig. 3, a case where the air pressure was controlled so that the force applied to the brake after the stop could be within the range of ±4N is shown in Fig. 8(a). To prevent the displacement when the brake is released, the force applied to the brake should be smaller than the static friction of 10 N on the sliding part. However, in the system shown in Fig. 3, since the supply pressure of 0.2MPa was taken directly into the cylinder, the pressure could not be fine-adjusted and the displacement was not caused but persistent oscillation was caused within the strain. Through additional experiments, it was confirmed that the force applied to the brake should be controlled to the range of ±25N to prevent the persistent oscillation in the system shown in Fig. 3. However, since 25N is larger than the static friction of 10N on the sliding part, the displacement is inevitable when the brake is released.

Then, using the system shown in Fig. 6, a case where the air pressure is controlled so that the force applied to the brake after the stop could be within the range of ±4N is shown in Fig. 8(b). After the force applied to the brake was controlled to the range of ± 4N by fine-adjusting the air pressure, the rod could be retained even after the brake was released.

Experiment 3 : The experimental results are shown in Fig. 9. In the PDC, since the balance of the forces is achieved after the control object reaches the target position, no sudden motion is caused even after the brake is released. Therefore, when the next target position was given continuously, the control object moved to the next target position. When the internal pressure of the cylinder (the differential pressure between chamber A and chamber B of Fig.6 : Pressure) was read at this time, it was confirmed that the balance of pressures was achieved after the control object reached the target position. As a result of this experiment, the effectiveness of the method that the authors had proposed was confirmed.

Experiment 4 : The experimental results are shown in Fig. 10. This system allowed the good control even when the load was applied.

V. Conclusions

In the study described in this paper, the PDC was applied to the positioning control of a pneumatic cylinder and the positioning based on inherently safe design was realized. Also, by fine-adjusting the air pressure, the load was retained even after the brake was released.

The method that the authors proposed has main advantages as follows:

(1) It is possible to satisfy the inherently safe design by divided into four steps, and each step is carried out only after confirming the conditions for safety.

(2) Most conventional control methods aim to realize the moving operation ($x(t)=x_p$, $x'(t)=0$) and the balancing operation ($F(t)=0$) at the same time. On the other hand, in the PDC, the balance of the forces is achieved in the hold state after moving operation, and therefore, the displacement does not occur in the balancing operation.

(3) When a brake is used, the high-rigidity positioning can be realized. Generally, to retain a large load by using a brake alone, a large brake force is required. However, when the force applied to the brake is detected and the air pressure is fine-adjusted accordingly, only a small brake force is required for retaining the load and controlling the pneumatic cylinder.

(4) When the system is improved and the air pressure is fine-adjusted, the precision of the balancing operation can be raised.

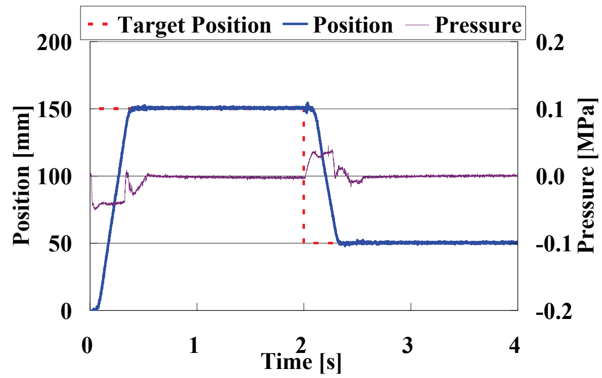


Fig. 9. Experiment 3.

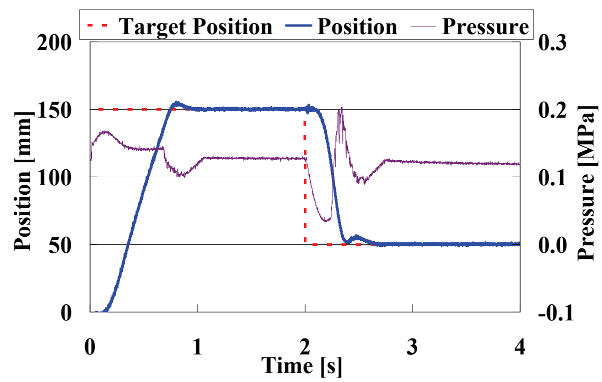


Fig. 10. Experiment 4.

(5) One of the causes that make it difficult to achieve the high-precision positioning control of pneumatic cylinders is that it is difficult to obtain a precise characteristic model. However, the PDC requires no such mathematical model.

The basic PDC sets importance on the safety, rather than the control performance. In the future, the control performance will be improved and it will be compared with the conventional methods. Also, since this control system is high in safety, the application to service robots to be used in contact humans is prospective.

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