A Study on the Hydraulic Cylinder with built-in Displacement and Thrust Control Function

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Abstract: A novel actuator with built-in the displacement and the thrust control function is presented in this paper. This actuator is a kind of compact hydraulic cylinder system which consists of a hydraulic cylinder, a spool, a sleeve, a mechanical feedback mechanism and a stepping motor. The displacement and thrust is in proportion to the rotational angle of stepping motor by the mechanical feedback. In order to investigate characteristics of this actuator, simulation study and preliminary experiments are conducted. Through the preliminary experiment this actuator is very effective in the control for displacement and thrust. Also, it became obvious that the stability of system can be adjusted by using the restrictor with the effect of velocity feedback. Furthermore, this paper explained that a flexible compliance control could be realized by adjusting the feedback weighting in the actuator.

Keywords: Hydraulic cylinder, Displacement control, Thrust control, Compliance control

1. INTRODUCTION

When the controls of displacement, thrust and compliance are carried out with the conventional hydraulic actuator that contacts with the environment, the measurement of displacement and thrust by sensor is necessary. Consequently the control systems require highly accurate servo valve, sensors and controllers to form a built-in cylinder system. Therefore, their system is very complicated and their size is relatively large and their costs are relatively high.

In this study, a "DiThCo cylinder"[1] has been developed as a novel hydraulic actuator to realize simplicity and miniaturization of the complicated hydraulic system that contains of the displacement and the thrust and the compliance control. In the term "DiThCo cylinder", the "Di" is abbreviation of "Displacement" and the "Th" is abbreviation of "Thrust" and the "Co" is abbreviation of "Compliance". Therefore, the DiThCo cylinder means a hydraulic cylinder with built-in the displacement and the thrust and the compliance control function.

In the DiThCo cylinder, a mechanical feedback is used in order to simultaneously control the piston displacement and thrust to be in proportion to the rotational angle of stepping motor. Furthermore, the flexible compliance control can be realized by adjusting the feedback weighting *m* in the DiThCo cylinder.

In the conventional digital electro-hydraulic cylinder, a ball-screw [4] was used for mechanical feedback mechanism. In the DiThCo cylinder, a compact steel belt was used for mechanical feedback mechanism instead of the ball-screw to realize the miniaturization of size.

The authors already developed a " spool-in-cylinder " [2, 3] to realize the displacement control. In comparison with the "spool-in-cylinder", the DiThCo cylinder have not only built-in the displacement control function, but also built-in the thrust control and the compliance control functions.

2. STRUCTURE OF DiThCo CYLINDER

Fig.1 shows a schematic diagram of the DiThCo cylinder system. It consists of a stepping motor, a 3-way spool type directional control valve with a spool and a mobile sleeve, a hydraulic cylinder, and a mechanical feedback mechanism. Since the DiThCo cylinder is approximately 103[mm] in length, and 57[mm] in height, with a maximum stroke of 40[mm], the structure of DiThCo cylinder is very compact.

The hydraulic circuit is a differential circuit and the area ratio of both piston sides is roughly 2:1.

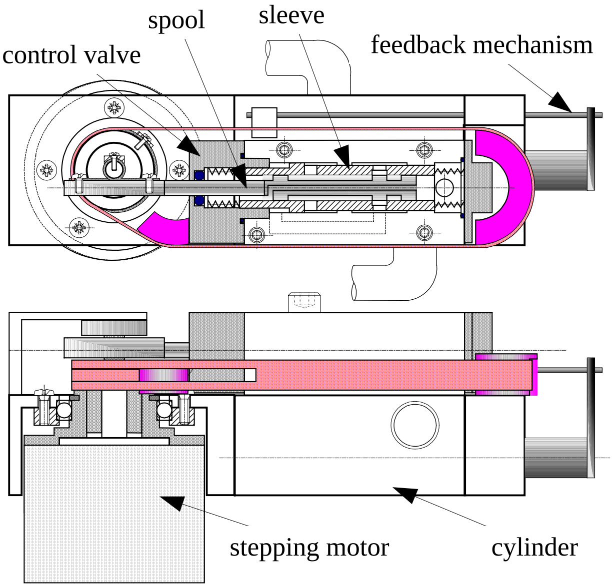

Fig.1 Schematic configuration of DiThCo cylinder

3. DISPLACEMENT CONTROL

3.1. Displacement Control Principle by Mechanical Feedback

In the hydraulic DiThCo cylinder, a mechanical feedback is used in order to control the piston displacement to be in proportion to the rotational angle of stepping motor. Fig.2 is a schematic diagram to explain the principle of mechanical feedback. In Fig.2, the mechanical feedback mechanism consisted of a stepping motor, a spool valve, a feedback pulley, a cylinder and a steel belt. The feedback pulley is fixed with the stepping motor body. The feedback pulley and the cylinder rod, the stepping motor and the spool are linked together through the steel belt.

When the stepping motor rotates in counterclockwise, the spool is pushed into the right side, which opens the restrictor orifice of supply pressure p_s and the piston extends. At this time, the steel belt linked with the piston pulls the feedback pulley and the stepping motor body to rotate in clockwise and drawn out the spool to the left side. Therefore spool returns to the neutral position, which closes the restrictor orifice of supply pressure p_s and the piston stops.

When the stepping motor rotates in clockwise, the driving principle is same as statement above.

Using such a mechanical feedback mechanism, the mechanical feedback is realized so that the piston displacement is in proportion to the rotational angle of stepping motor.

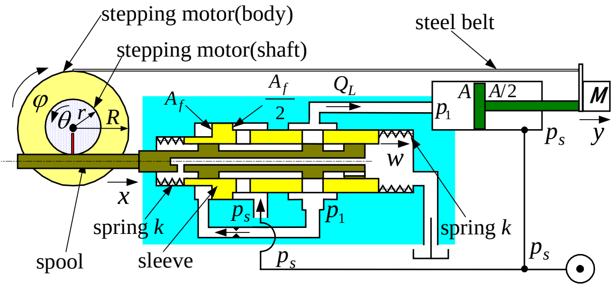

Fig.2 Principle of displacement control

3.2. Basic Equation of Displacement Control

The following discussion will be concentrated on the case when there is the inertia load M and damping load B.

The flow rate go through spool valve is expressed in Eq. (1).

$$Q_L = \mathrm{sgn}(p_s - \mathrm{sgn}(x-w)2p_L)C_d \pi d(x-w)\sqrt{\frac{\left|p_s - \mathrm{sgn}(x-w)2p_L\right|}{\rho}} \quad (1)$$

where x is the spool displacement, w the sleeve displacement, C_d the flow coefficient, p_s the supplied oil pressure, and ρ the mass density of oil.

When the compressibility of the working fluid is considered, the continuity equation is

$$A\frac{dy}{dt} = Q_L - \frac{V_1}{K_b}\frac{dp_1}{dt} \quad (2)$$

where A is the effective cross-sectional area of the cylinder, V_1 the volume in the cylinder piston side, p_1 the oil pressure in the cylinder piston side, and K_b the bulk modulus of the oil.

The load pressure is defined as follows.

$$p_L = p_1 - \frac{p_s}{2} \quad (3)$$

In the steady state, the equation of sleeve motion is written as

$$2kw = A_f p_1 - \left(\frac{A_f}{2}\right)p_s = A_f p_L \quad (4)$$

where w is the sleeve displacement, k the sleeve spring constant, and A_f the effective cross-sectional area of the sleeve.

The relation of the spool displacement $x = r(\theta - \varphi)$, the input of the stepping motor $z = r\theta$ and the piston displacement $y = R\varphi$ is shown in Eq. (5).

$$x = r(\theta - \varphi) = z - \frac{y}{(R/r)} \quad (5)$$

where θ is the rotational angle of stepping motor, φ the rotational angle of feedback pulley, R the rotational radius of feedback pulley, and r the rotational radius of stepping motor shaft.

The equation of piston motion is expressed in Eq. (6).

$$M\frac{d^2y}{dt^2} + B\frac{dy}{dt} = Ap_1 - \left(\frac{A}{2}\right)p_s = Ap_L \quad (6)$$

3.3. Linear Approximation Model of Displacement control

In the DiThCo cylinder, if the flow rate characteristic Eq. (1) is linearized in the vicinity of operating point, Eq. (7) is derived.

$$\Delta Q_L = k_1\Delta(x-w) - k_2\Delta p_L \quad (7)$$

where linear approximation parameter k_1, k_2 are flow rate gain and pressure flow rate coefficient respectively.

The Laplace transform is conducted on Eqs.(2), (3), (4), (5), (6) and (7). The transfer function from the input of the stepping motor Δz to the piston displacement Δy is shown in Eq.(8).

$$G(s) = \frac{\Delta y}{\Delta z} = \frac{Y}{Z} = \frac{k_1}{As + \frac{1}{A}\left(\frac{V_1}{k_b}s + k_2 + \frac{k_1 A_f}{2k}\right)\left(Ms^2 + Bs\right) + \frac{r}{R}k_1} \quad (8)$$

The block diagram based on Eq.(8) is shown in Fig.3.

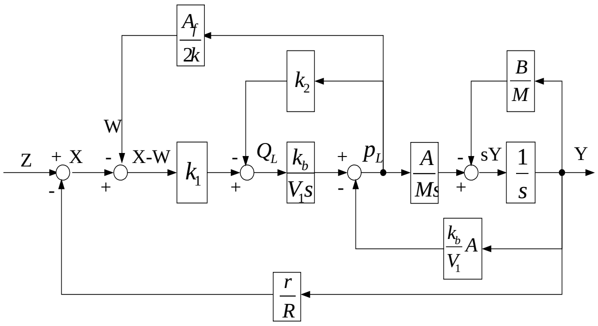

Fig.3 Block diagram of displacement control

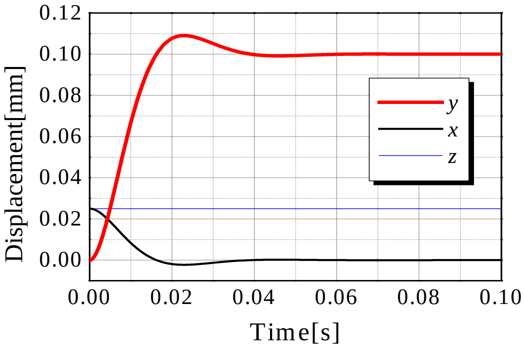

Fig.4 Results of Linear Simulation

By using the linear approximation model, the step response of the displacement control is shown in Fig.4. Since the step response of the displacement y is fast, the cylinder can follow-up the desired value quickly. However there is an overshoot in the response of the DiThCo cylinder displacement y.

3.4. Non-Linear Simulation

In the linear model analysis, the perturbation in the vicinity of the operating point was considered. However, actually the parameters vary in the huge range. So the non-linear simulation is necessary. On the basis of Eqs.(1), (2), (3), (4), (5) and (6), the step response was investigated, and the results are shown in Fig.5. As for non-linear simulation result, the response of the cylinder displacement y is fast, but the overshoot is occurred. This result of non-linear simulation agrees with linear analysis.

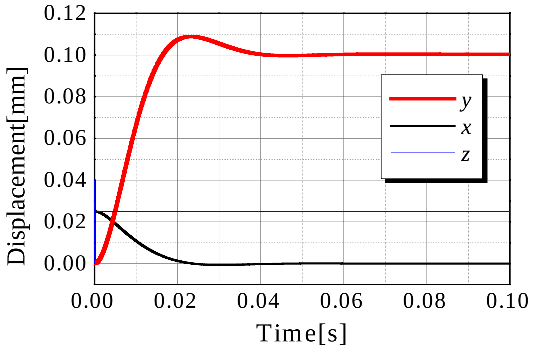

Fig.5 Results of non-linear simulation

3.5. Adjustment of System Stability on the Displacement Control

The Eq.(6) is basic equation of piston motion. However, the overshoot is occurred. To improve this phenomenon, as shown in Fig.6, the restrictor is added in the cylinder rod side and the damping effect such as velocity feedback is given. In this case the equation of piston motion is written as Eq. (9).

$$M\frac{d^2y}{dt^2}+B\frac{dy}{dt}=A\left(p_1-\frac{p_2}{2}\right) \qquad (9)$$

The pressure in cylinder rod side is

$$\dot{p}_2=\frac{k_e}{V_2}\left(\frac{A}{2}\dot{y}-Q_2\right) \qquad (10)$$

where V_2 is the volume in the cylinder rod side.

The flow rate of cylinder rod side is expressed in Eq. (11).

$$Q_2=C_dA_2\,\mathrm{sign}(p_2-p_S)\sqrt{\frac{2\left|p_2-p_S\right|}{\rho}} \qquad (11)$$

The load pressure is defined as follows.

$$p_L=p_1-\frac{p_2}{2} \qquad (12)$$

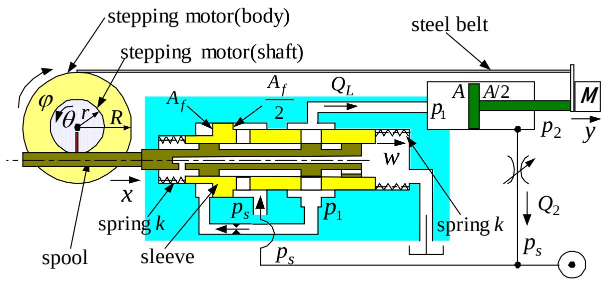

Fig.6 Principle of displacement control with restrictor

On the basis of Eqs.(1), (3), (4), (5), (9) , (10) , (11) and (12), the step response was investigated by simulation, and the results are shown in Fig.7. The response of the piston displacement y without restrictor is fast, but the overshoot is occurred. The response of the piston displacement y with restrictor in the rod side is slightly slow, but the overshoot is improved. It is clear that the stability of system can be adjusted by using the restrictor with the effect of velocity feedback.

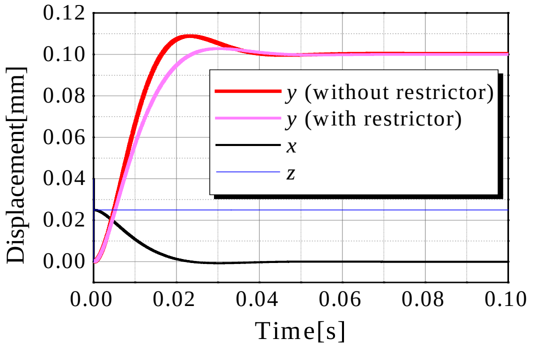

Fig.7 Results of simulation

3.6. Relationship between Piston Displacement y and Thrust f in the Steady State

In the steady state, the relationship between the piston displacement y and the thrust f is

$$f=p_LA=K_S(R\theta-y) \qquad (13)$$

where K_S is spring constant of the natural system(i.e. system-spring-constant), which is defined as follows.

$$K_S=2k\left(\frac{A}{A_f}\right)\left(\frac{r}{R}\right) \qquad (14)$$

From Eq. (13), it is clear that the DiThCo cylinder has system-spring-constant K_s and the output of thrust f is in proportion to the displacement reference value (which is R times of the rotational angle of stepping motor) and the difference of the real piston displacement y.

4. THRUST CONTROL

In order to simplify explanation, as shown in Fig.8, take a case that the DiThCo cylinder contacts with the hard environment (such as wall) for example. The principle of thrust control is shown in Fig.8.

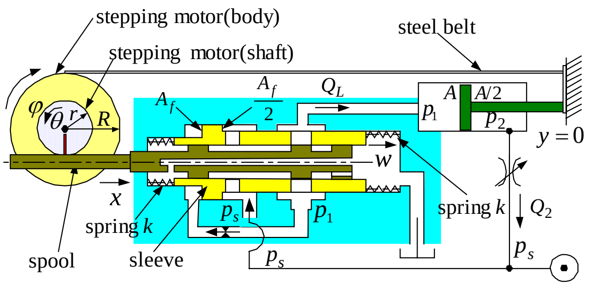

Fig.8 Principle of thrust control

When the stepping motor rotates in anti-clockwise, the spool is pushed into the right side and the restrictor orifice of supply pressure p_s opens. The pressure p_1 flows into the cylinder and the thrust is occurs from the cylinder. At this time, the pressure p_1 flows into the left side of the sleeve and the sleeve is moved to the right side. When the sleeve displaces same distance as spool, the restrictor orifice of supply pressure p_s is closed and the thrust f is determined. Since this sleeve is supported with the spring of both its sides, the thrust f is in proportion to sleeve displacement w.

When the stepping motor rotates in clockwise, the driving principle is same as statement above.

In this case, because $y = 0$, the relationship between the spool displacement *x*, input of stepping motor *z*, and sleeve displacement *w* is written as Eq. (15).

$$x = z = w = r\theta \qquad (15)$$

Therefore, the equation for thrust control is written as Eq. (16). The Eq.(16) is equivalent to the Eq.(13) in the case of $y = 0$.

$$f = Ap_L = 2k\left(\frac{A}{A_f}\right)z = K_s R\theta \qquad (16)$$

From Eq. (15) and Eq. (16), it is clear that the output of thrust f is in proportion to the rotational angle of stepping motor in the case of $y = 0$.

5. COMPLIANCE CONTROL

In the displacement and the thrust control, it is confirmed that the DiThCo cylinder has system-spring-constant K_S. If it is able to adjust this system-spring-constant K_S, it would be possible to control the compliance of the system. Here, the compliance control is a technique to control a system flexibly according to the external force when DiThCo cylinder contacts with the environment.

The principle of compliance control of DiThCo cylinder is shown in Fig.9.

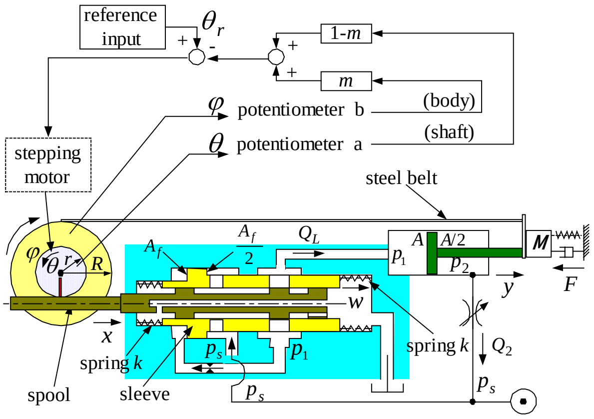

Fig.9 Principle of compliance control

Here, the feedback weighting of potentiometers a and b are defined as $(1-m)$ and m respectively, the thrust f of DiThCo cylinder is determined by

$$f = K_s'(R\theta_r - y) \qquad (17)$$

where θ_r is the reference of the rotational angle of stepping motor, *m* is the feedback weighting, and K_s' is defined as Eq.(18).

$$K_s' = \frac{K_s}{1-m} \qquad (18)$$

Fig.10 shows the relationship between the K_s' and the *m*.Through the Eq.(17) and Fig.10, the conclusion is obtained as follows.

This K_s' is determined by

$$\begin{cases} K_S' > K_S & when\ 0 < m < 1 \\ K_S' = K_S & when\ \quad m = 0 \\ K_S' < K_S & when\ \quad m < 0 \end{cases} \qquad (19)$$

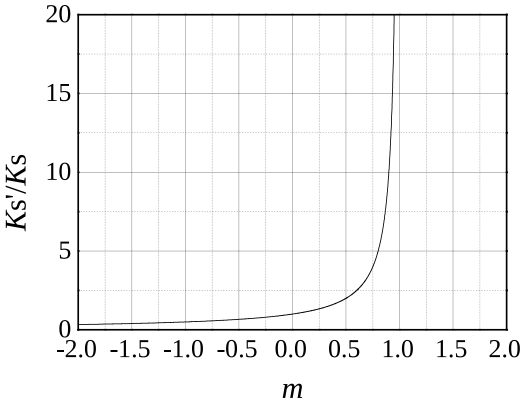

Fig.10 Relationship between the *Ks*'/*Ks* and the *m*

When $K_S' > K_S$, the larger the parameter *m*, the smaller the compliance, and thus the DiThCo cylinder becomes a strict system. The smaller the parameter *m*, the larger the compliance, and thus the DiThCo cylinder becomes a flexible system.

When $K_S' = K_S$, the DiThCo cylinder becomes the displacement control system shown in section 3.6. In this case, the DiThCo cylinder has a system-spring-constant K_s shown in Eq.(13).

When $K_S' < K_S$, the DiThCo cylinder becomes a flexible system. In this case, the compliance is larger than the system shown in section 3.6.

As stated above, the flexible compliance control can be realized by adjusting the feedback weighting *m* in the DiThCo cylinder. Namely the system spring constant is to be changed with $K_s' = K_s/(1-m)$ from K_s.

6. EXPERIMENTAL RESULT AND CONSIDERATION

6.1. Static Characteristics of Displacement

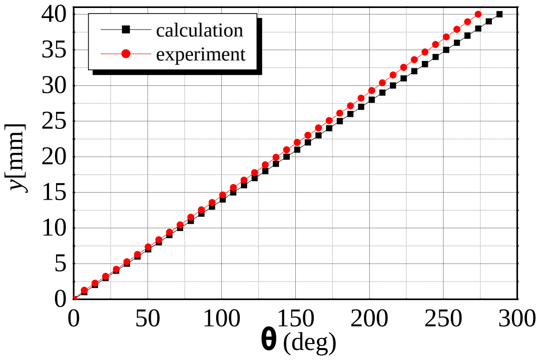

Fig.11 Relationship between the rotational angle of the stepping motor and the displacement

This experiment was conducted to examine static characteristics of DiThCo cylinder displacement *y*.

In this case, the input is the rotational angle θ of stepping motor, and the output is the cylinder displacement *y*. Theoretically the cylinder displacement *y* will increase by

1mm when the rotational angle θ is increased by 7.2 degrees. Fig.11 shows good linearity characteristic that the output is in proportion to the input when the cylinder is in unloaded. However, there exists difference between the calculation and the experimental result. Since the diameter of feedback ring becomes large when the steel belt thickness is taken into consideration, the feedback gain changes slightly. In this experiment, when the input θ is increased by 7.2 degrees the average of the output increment is 1.05 mm that is larger than the calculated output increment. This problem can be improved by adjusting the diameter of feedback ring. Therefore the DiThCo cylinder can be used as an actuator for a displacement control system.

6.2. Step Response

This experiment was conducted to examine step response of DiThCo cylinder displacement *y*. The spool displacement x and the cylinder displacement y are measured with potentiometers. When the rotational angle θ of stepping motor is 7.2 degrees, the step responses are shown in Fig.12. The response of the piston displacement y is fast and the overshoot is improved with the restrictor in the rod side. Therefore, this result shows the successful operation of the DiThCo cylinder, and good correspondence with the simulation result of Fig.7. There is dead time of 0.01s in Fig.12, this is considered as a slack of the steel belt and the delay time of stepping motor.

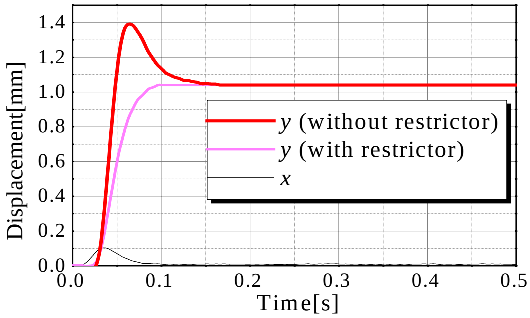

Fig.12 Step response of DiThCo cylinder

6.3. Thrust Control

This experiment was conducted to examine static characteristics of DiThCo cylinder thrust f.

In this case, the input is the rotational angle θ of stepping motor, and the output is the cylinder thrust f.

When the input is 0.72 degrees and the supply pressure is 4MPa, the calculated cylinder thrust is 0.534kgf and it is saturated with ± 35 [kgf].

Fig.13 shown experiment results for the relationship between the rotational angle θ of stepping motor and the cylinder thrust f. A linearity characteristic that the output thrust f is in proportion to the input θ is obtained. However, in comparison with the calculation, the experimental result has some difference and is saturated with ± 30 [kgf]. This is considered that this is caused on account of supply pressure loss which is occurred by the flow leakage of the spool. This program can be settled by manufacturing highly precise spool valve. Therefore the DiThCo cylinder can also be used as an actuator for a thrust control system.

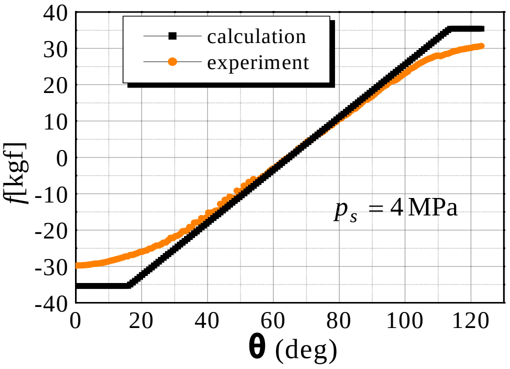

Fig.13 Relationship between the rotational angle of stepping motor and the thrust of DiThCo cylinder

7. CONCLUSION

In this study, a novel hydraulic actuator (i.e. DiThCo cylinder) is developed and the experiment with the prototype was conducted. The typical feature of DiThCo cylinder is its built-in displacement, thrust control and compliance control functions. The second positive feature of DiThCo cylinder is its simplicity, miniaturization structure. Analytical studies and computer simulations are executed to verify the effects on the performance. The simulation and the experimental results are summarized as follows.

In the displacement control, with a mechanical feedback mechanism, the DiThCo cylinder displacement is linear in relation to the input of stepping motor. The step response of displacement is fast and the overshoot is improved by using the restrictor with the effect of velocity feedback.

In the thrust control, with a sleeve and the spring of both its sides, the DiThCo cylinder thrust is in proportion to the input of stepping motor in the case of $y = 0$.

In respect to the compliance control, only the operating principle is proposed in this study. It would be a future work to experiment of compliance control of DiThCo cylinder.

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