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EXPERIMENTAL STUDY OF FRICTION CHARACTERISTICS OF PNEUMATIC CYLINDER

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Abstract. Understanding of friction characteristics of a pneumatic cylinder may contribute to efficient design of a pneumatic cylinder system. However, friction behaviors of a pneumatic cylinder have not completely been elucidated. In this paper, the steady-state and dynamic friction characteristics of three types of pneumatic cylinders are investigated in detail, and the effects of rod and piston packings on friction characteristics are also investigated using two types of lubricants, grease and oil. It is shown that the steady-state friction characteristic of the pneumatic cylinders with a good low speed performance is somewhat complicated compared to that of a standard type cylinder but can be expressed by a usual friction model with two velocity-range dependent parameters. It is also shown that the friction characteristics are dominated by piston packing and are strongly affected by lubricant type.

Keywords: Friction, Pneumatic cylinder, Rod packing, Piston packing, Grease, Oil, Steady-state, Dynamic

INTRODUCTION

Nonlinear friction characteristics of a pneumatic cylinder make its dynamics rather complex and may deteriorate its control performance. Investigation and modeling of the friction characteristics of a pneumatic cylinder may contribute to predicting and improving its control performance. Some papers have reported the friction between the seals and the cylinder bore [1], the occurrence of stick-slip motion [2], the friction force in a labyrinth-sealed pneumatic cylinder [3], an elastomeric piston seal for low-friction [4] and the dynamic friction behaviors of pneumatic cylinders [5]. Friction behavior of pneumatic cylinders, however, has not been fully made clear yet. There are some types of pneumatic cylinders such as standard type and types with a good low speed performance in which a special grease is used. The friction characteristic of a standard type pneumatic cylinder has a typical negative resistance characteristic at low velocities, but no negative resistance characteristic was observed for the pneumatic cylinders with a good low speed performance [6]. However, a negative resistance characteristic may be observed at very low velocities, but no measured data have been published.

In a pneumatic cylinder, friction force is generated between rod and rod packing and between cylinder tube and piston packing. However, the friction characteristics of the sliding parts of the rod and piston have not been examined separately, to the best of the authors' knowledge.

In the present study, the steady-state friction characteristic of standard type and low speed type pneumatic cylinders are examined including very low velocities. Friction characteristics of the rod and rod packing and those of the cylinder tube and piston packing are separately investigated experimentally using a standard type pneumatic cylinder. Moreover, the effect of lubricant type on the friction characteristics is examined.

EXPERIMANTAL APPARATUS AND METHOD

The experimental apparatus is shown in **FIGURES 1** and **2**. It consists of a pneumatic cylinder under test and a stepper motor with a rack and pinion mechanism. The pneumatic cylinder is driven at precisely controlled velocities by the stepper motor. A load cell connects the piston rod and the fixed plate and is used to measure the force, F_L acting on the pneumatic piston. The pneumatic cylinder is attached to a plate fixed to the stepper motor.

In the experiments to examine the steady-state friction characteristics, three types of pneumatic cylinders produced by SMC Corporation were used and their specifications are shown in **TABLE 1**. They are of the same size but have different grease materials and surface treatment of tube.

In the experiments to examine the effects of the rod packing and piston packing, the tube of the pneumatic cylinder of the standard type was cut into two parts: a longer tube (tube 1) and a shorter one (tube2), as shown in **FIGURE 3**. When measuring the friction characteristics of the rod and rod packing, the tube 1 was removed, as shown in **FIGURE 4**. On the other hand, when measuring the friction characteristics of the cylinder tube and piston packing, the tube 2 was removed.

In the experiments to examine the effect of lubricant, a grease and a lubricating oil were used as lubricant. These experiments were conducted in the state that both of the rod packing and piston packing were mounted. The grease used was the same as that used in the standard type pneumatic cylinder and was spread evenly on the rod packing surface and piston packing surface. The lubricating oil was COSMO HYDRO HV32, which is a high viscosity index type of abrasion-proof hydraulic oil and is superior in the compatibility with packing materials. After finished measuring the friction characteristics of grease lubrication, the grease was wiped off using a cleaner that has a little influence on the packing materials and the lubricating oil was applied to the rod packing surface and piston packing surface.

The velocity, v, of the pneumatic piston was measured using a laser displacement meter. The values of the velocity and the force from the sensors were read into a data logger. The friction force, F_r, was obtained from the equation of motion of the pneumatic piston as follows:

$$F_r = p_1A_1 - p_2A_2 + F_L - ma. \tag{1}$$

where m is the total mass of the pneumatic piston, p_1 and p_2 are the pressures in the two cylinder chambers, A_1 and A_2 are the pressure-receiving areas of the piston, and a is the acceleration of the piston.

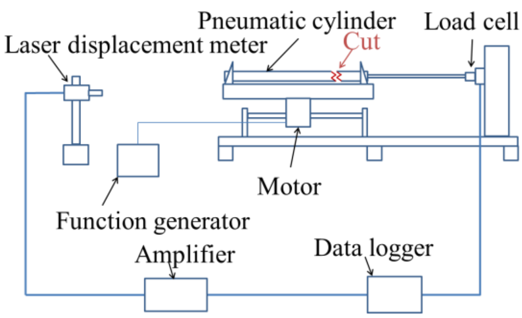

FIGURE 1. Schematic of Experimental Apparatus

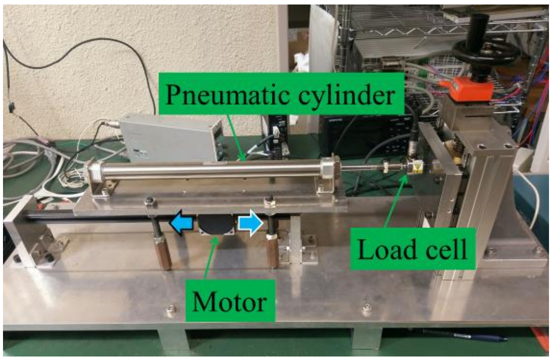

FIGURE 2. Photograph of Experimental Apparatus

TABLE 1. Pneumatic Cylinders Tested

Type	Catalog type name	Piston dia.	Rod dia.	Stroke	Catalog recommendation velocity
1	Standard type (CM2)	25 mm	10 mm	300 mm	50 - 750 mm/s
2	Smooth type (CM2Y)				5 - 500 mm/s
3	Low Speed type (CM2X)				0.5 - 300 mm/s

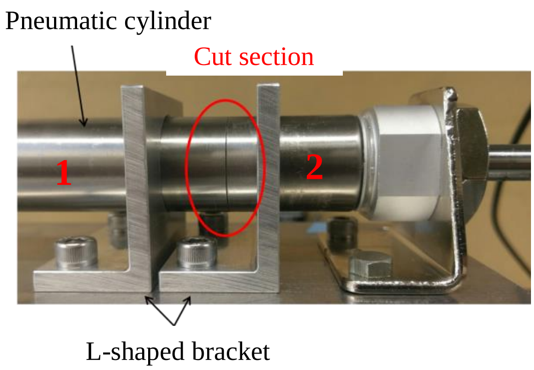

FIGURE 3. Photograph of Cut Section of Pneumatic Cylinder

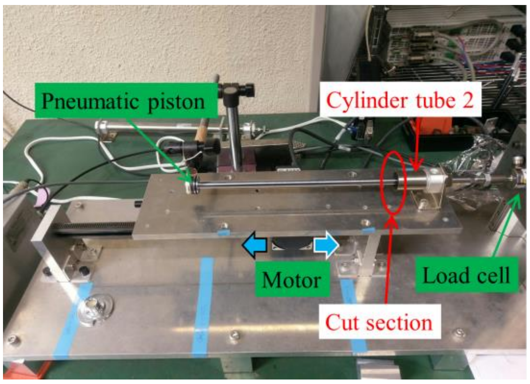

FIGURE 4. Measurement of Friction Force Caused by Rod Packing

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RESULTS AND DISCUSSION

Steady-State Characteristics

FIGURE 5 shows the steady-state friction characteristics of the three pneumatic cylinders. The positive and negative velocities correspond to the extending and retracting strokes, respectively. The steady-state friction characteristic was obtained by plotting the steady values of friction force at different constant velocities in the range from ±0.01 to ±120 mm/s. In the results of the previous study [6] in which the velocity was varied from ±1.2 to ±120 mm/s, a negative resistance characteristic of friction was observed in Type 1 cylinder and was not observed in Type 2 and Type 3 cylinders. However, it is seen from **FIGURE 5** that a negative resistance characteristic of friction is observed in all the pneumatic cylinders.
The steady-state friction characteristic is expressed by

$$F_{rss} = F_C + (F_S - F_C)e^{-(v/v_S)^n} + \sigma_2 v. \quad (2)$$

where F_C is the Coulomb friction force, F_S is the maximum static friction force, v is the relative velocity between contact surfaces, v_S is called the Stribeck velocity, n is an appropriate exponent, and σ_2 is the viscous friction coefficient. **FIGURE 6** shows the experimental result of steady-state friction characteristics of Type 1 cylinder and the result calculated by Eq. (2) using the values shown in **TABLE 2**, which were obtained by the least squares method. The horizontal axis is expressed on a logarithmic scale to clearly show the variation of friction force at low speeds. The steady-state friction characteristic of Type 1 cylinder can be expressed by the ordinary friction model, Eq. (2). The steady-state friction characteristics of Type 2 and Type 3 cylinders are shown in **FIGUREs 7**and **8**, respectively and cannot be modeled by Eq. (2) as shown by blue curves. However, if the values of two parameters, F_C and σ_2, are varied according to the velocity range, the measured friction characteristics can well be modeled by Eq. (2) as shown by green curves. The values of friction model parameters for Type 2 and Type 3 are shown in **TABLEs 3** and **4**, respectively.

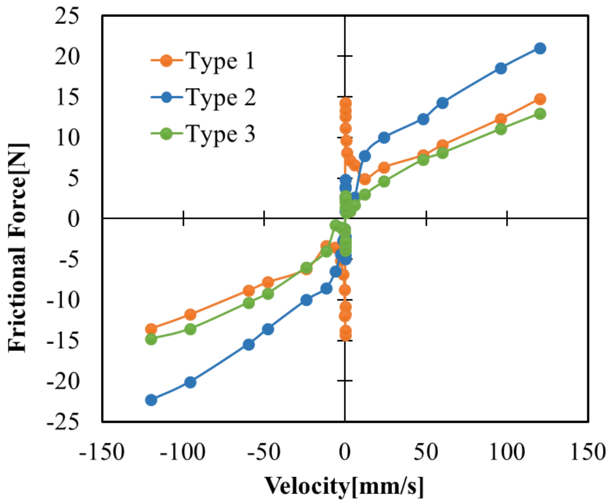


FIGURE 5. Steady-State Friction Characteristics of Three Test Cylinders

TABLE 2. Values of Steady-State Friction Model Parameters (Type 1)

F_S [N]	F_C [N]	v_S [m/s]	σ_2 [N/(m/s)]	n [-]
15.5	2.4	0.003	110	0.43

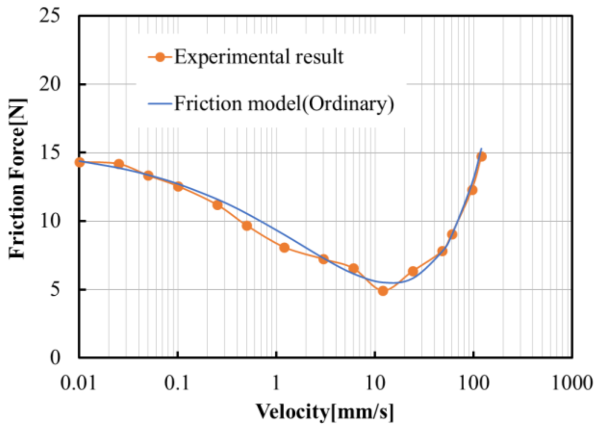


FIGURE 6. Comparison between Measured and Calculated Steady-State Friction Characteristics (Type 1)

TABLE 3. Values of Steady-State Friction Model Parameters (Type 2)

	F_S [N]	F_C [N]	v_S [m/s]	σ_2 [N/(m/s)]	n [-]
v < 12 mm/s	4.9	1	0.0001	170	2.8
v ≧ 12 mm/s		6.4		125	

TABLE 4. Values of Steady-State Friction Model Parameters (Type 3)

	F_S [N]	F_C [N]	v_S [m/s]	σ_2 [N/(m/s)]	n [-]
v < 12 mm/s	2.7	0.7	0.00075	104	1.5
v ≧ 12 mm/s		2.2		94	

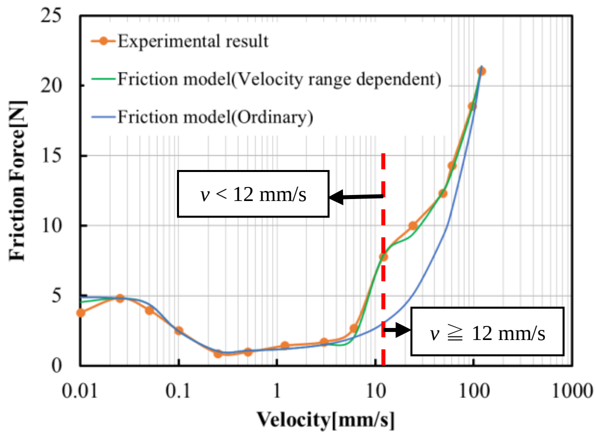


FIGURE 7. Comparison between Measured and Calculated Steady-State Friction Characteristics (Type 2)

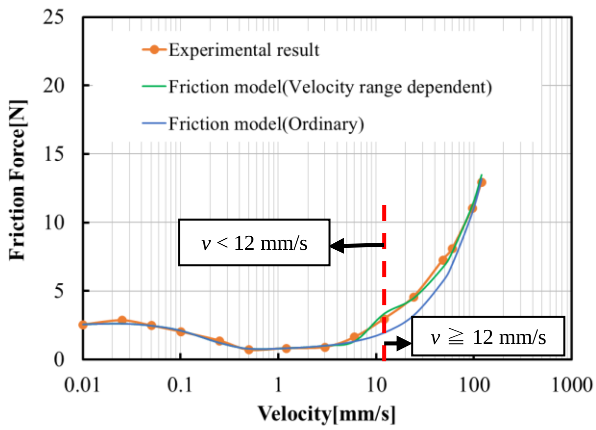
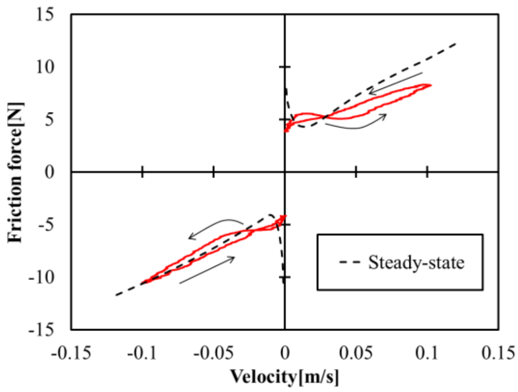


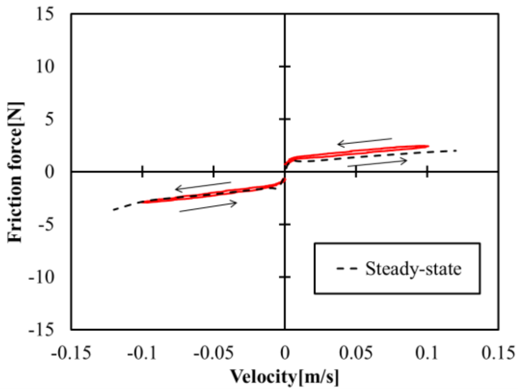
FIGURE 8. Comparison between Measured and Calculated Steady-State Friction Characteristics (Type 3)

Dynamic Characteristics

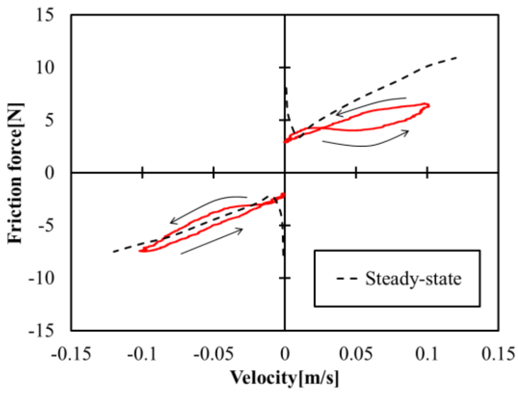
Dynamic friction characteristics of Type 1 cylinder during one cycle of continuous sinusoidal velocity variations at the frequency of 2 Hz are shown in **FIGURE 9** and are compared with the steady-state friction characteristics. Friction force was measured under three conditions that both of the rod and piston packings were incorporated into the cylinder (**FIGURE 9** (a)) and one of the two packings was removed (**FIGUREs 9** (b) and **9** (c)). As can be seen from **FIGURE 9** (a), the dynamic friction force is smaller to some degree than the steady-state friction force in the extending stroke and is almost the same as that in the retracting stroke. The direction of hysteretic loop is counterclockwise in both strokes. These behaviors do not agree with the behaviors reported by Tran et al. [6], though the reason for the different behaviors is not clear. The dynamic friction force caused by the rod packing is much smaller than the entire friction force and almost traces the steady-state friction characteristic as shown in **FIGURE 9** (b), while the magnitude and dynamic behavior of the friction force caused by the piston packing shown in **FIGURE 9** (c) are similar to those shown in **FIGURE 9** (a) in both strokes. **FIGURE 9** shows that piston packing dominates the friction characteristics of Type 1 cylinder.



(a) Entire Friction Force (Rod Packing + Piston Packing)



(b) Friction Force Caused by Rod Packing



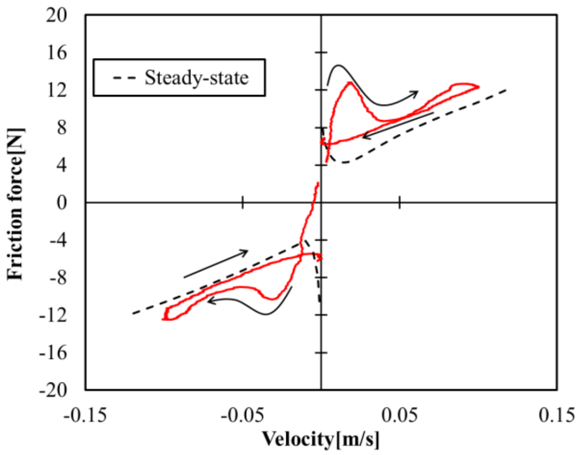
(c) Friction Force Caused by Piston Packing

FIGURE 9. Dynamic Friction Characteristics (Type 1, Frequency of Velocity Variation = 2 Hz)

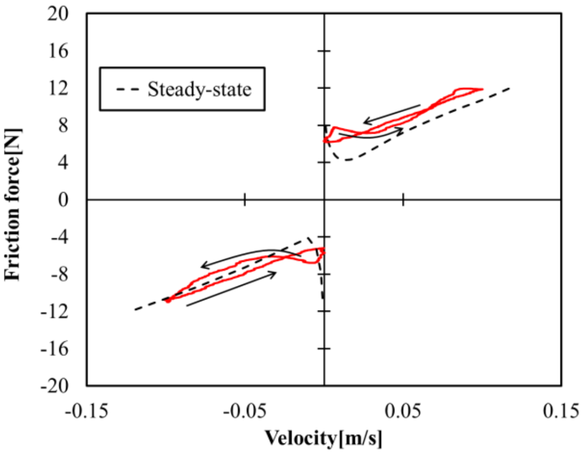
FIGURE 10 shows the effect of lubricant on steady-state and dynamic friction characteristics of Type 1 cylinder. The steady-state friction characteristic was much different between the two lubricants. The negative resistance range is much smaller for grease lubrication than for oil lubrication and the slope of the Stribeck curve in the fluid lubrication regime is larger for grease lubrication than for oil lubrication. These differences result from the difference in the magnitude of viscosity between the two lubricants.

The dynamic friction characteristic was measured during the first and second cycles of sinusoidal velocity variation after 5 minutes dwell period. Because the lubricant is squeezed out of the gaps between the sliding surfaces during the dwell period, a maximum friction force (break-away force) was observed immediately after the onset of the piston motion (**FIGUREs 10**(a),(c)) and the same friction behavior was repeated after the first cycle (**FIGUREs 10**(b),(d)). For grease lubrication, the break-away force was relatively large and the friction force decreased quickly from the maximum value and varied almost along or slightly counterclockwise around the steady-state friction characteristic as shown **FIGUREs 10** (a) and (b). On the other hand, for oil lubrication, the dynamic friction force varied clockwise around the steady-state friction characteristic over the velocity variation range in the same way as in hydraulic cylinders [7, 8].

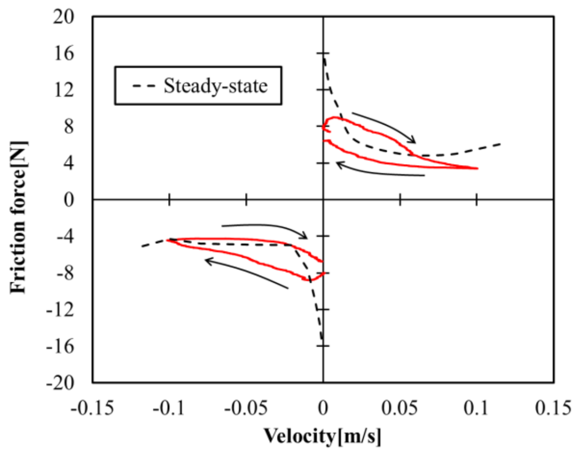
As can be seen from **FIGURE 10**, the dynamic friction characteristics are strongly affected by the type of lubricant. It was confirmed that the difference in dynamic friction characteristics between pneumatic cylinders [6] and hydraulic cylinders [7, 8] results from the difference in rheological property between grease and oil.



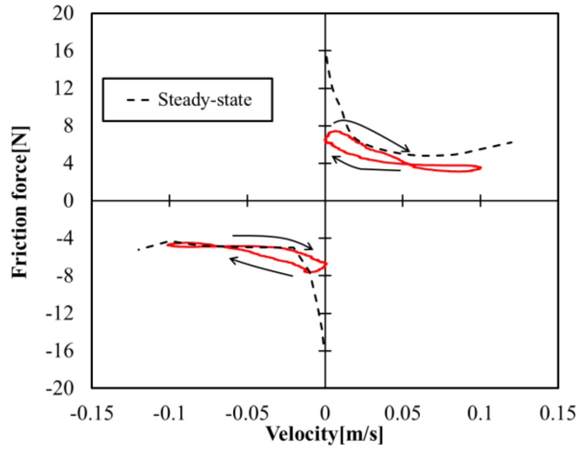
(a) Grease Lubrication (First Cycle)



(b) Grease Lubrication (Second Cycle)



(c) Oil Lubrication (First Cycle)



(d) Oil Lubrication (Second Cycle)

FIGURE 10. Dynamic Friction Characteristics (Type 1, Frequency of Velocity Variation = 2 Hz)

CONCLUSIONS

The steady-state friction characteristics of three types of pneumatic cylinders are examined including very low speeds. The effects of the rod and piston packings and lubricant type on the steady-state and dynamic friction characteristics are investigated using one of the three pneumatic cylinders. The following conclusions can be drawn within the scope of this study:

・The steady-state friction characteristics of the pneumatic cylinders with a good low speed performance (Type 2 and Type 3) are somewhat complicated compared to that of a standard type cylinder (Type 1), but can be expressed by a usual friction model with two velocity-range dependent parameters.

・The friction characteristic of a pneumatic cylinder is dominated by piston packing.

・The dynamic friction characteristics of pneumatic cylinders are different from those of hydraulic cylinders resulting from the difference in rheological property of lubricant.

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