Friction and Vibration Characteristics of Pneumatic Cylinder

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Abstract

Efficient design of a pneumatic cylinder system is achieved by the clarification of the dynamic behaviors including nonlinear friction characteristics of the pneumatic cylinder. In the present study, the dynamic friction and vibration characteristics of a pneumatic cylinder are investigated experimentally and the relation between the friction characteristics and the vibration characteristics is discussed. In the experiments, the pneumatic cylinder was operated only in the upward motion. The piston speed was varied stepwise or sinusoidally to investigate the steady-state and dynamic friction characteristics and their effect on the vibration characteristics. At the mean velocity of 0.010 m/s, a stick-slip motion took place. According to the repeated velocity variations from zero to about 0.1 m/s, the friction force was oscillated. Finally, the effect of the dwell time on the dynamic friction characteristic was examined. It was seen that the break-away force increases with the increase of the dwell time but tends to approach a constant value asymptotically at the dwell time longer than 120 s.

Keywords: friction, vibration, pneumatic cylinder, dynamic behavior, stick-slip motion, break-away force

1 Introduction

This paper deals with an experimental investigation on friction and vibration of a pneumatic cylinder. Pneumatic cylinders are widely used in industry because of their relatively large output power to size ratio, easy operation, safety, etc. However, it is not easy to control the pneumatic cylinders precisely due to their highly nonlinear friction characteristics and the compressibility of air and, therefore, their applications are limited to point-to-point control operations. In order to achieve accurate positioning of a pneumatic cylinder, the nonlinear friction characteristics need to be made clear and expressed by a mathematical model. In addition, if a mathematical model for the friction characteristics is developed, the dynamic behaviors of a pneumatic cylinder system can be accurately predicted by simulation at its design stage. This contributes to reducing the time for design, designing a better controller, and to a better selection of components.

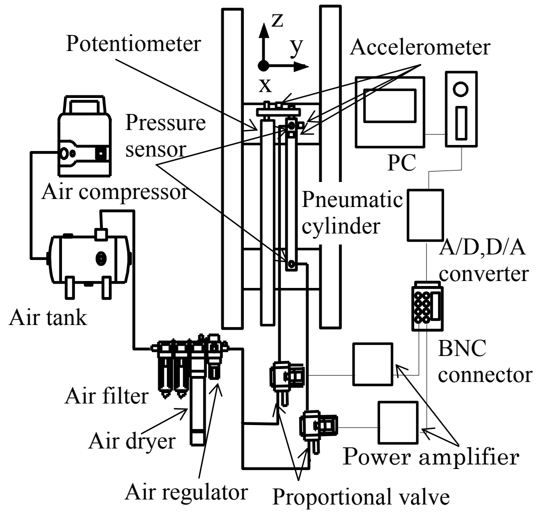


Fig.1 Schematic of experimental apparatus

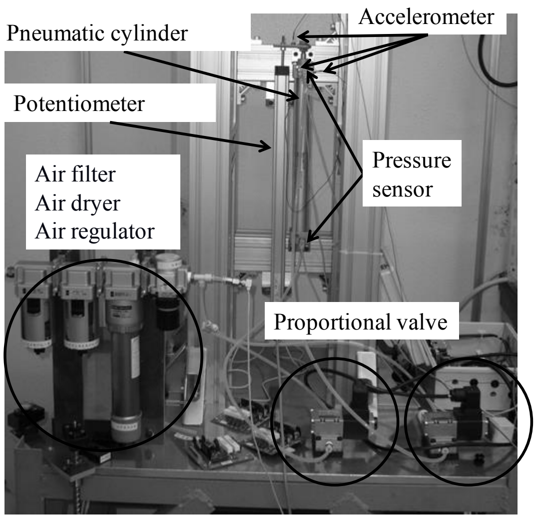


Fig.2 Photograph of experimental apparatus

Some papers have reported the characteristics of pneumatic cylinders, including the effect of nonlinear friction on pneumatic cylinder motion [1], the experimental and numerical study of the friction between the seals and the cylinder bore [2], and the occurrence of stick-slip motion [3]. Moreover, chaotic oscillations observed at low speed actuation of pneumatic cylinders have been examined [4]. Tran et al. have investigated the dynamic friction behaviors of pneumatic cylinders [5] but the experimental conditions were limited and vibration characteristics were not examined. Therefore, the nonlinear friction behaviors of pneumatic cylinders have not fully been examined and modeled yet.

In the present study, the dynamic friction and vibration characteristics of a pneumatic cylinder are investigated experimentally and the relation between the friction characteristics and the vibration characteristics of the pneumatic cylinder is discussed.

2 Experimental apparatus and method

The experimental apparatus is shown in **Figs.1** and **2**. A standard pneumatic cylinder, of which piston diameter, rod diameter, and stroke are 32 mm, 12 mm, and 300 mm, respectively, was used as a test cylinder. The test cylinder was fixed perpendicularly on a horizontal table. A potentiometer and two pressure sensors were used to measure the cylinder position and the pressures in the cylinder chambers. The vibrations of the piston in the *x*, *y*, *z*-directions were measured by three accelerometers glued on the cylinder.

In the experiments, the pneumatic cylinder was operated only in the upward motion. The air flow rate supplied to the cylinder was controlled by the proportional flow control valves. The piston speed was varied stepwise or sinusoidally to investigate the steady-state and dynamic friction characteristics and their effect on the vibration characteristics. The piston speed was obtained by approximately differentiating the position.

The friction force, F_r, is obtained from the equation of motion of the pneumatic piston as follows:

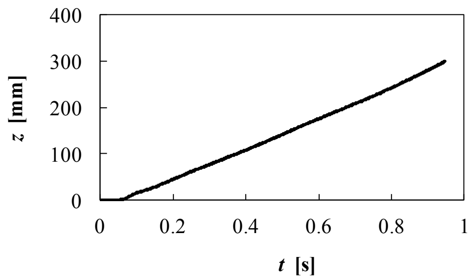
$$F_r = p_1 A_1 - p_2 A_2 - mg - ma \qquad (1)$$

where m is the 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, a is the acceleration of the piston, and g is the acceleration of gravity.

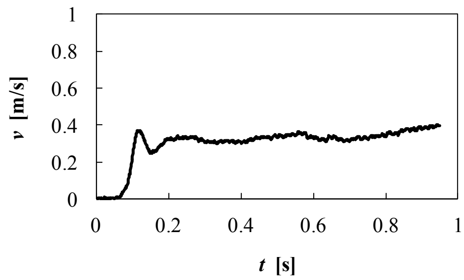
3 Results and discussion

3.1 The case for steady-state characteristics

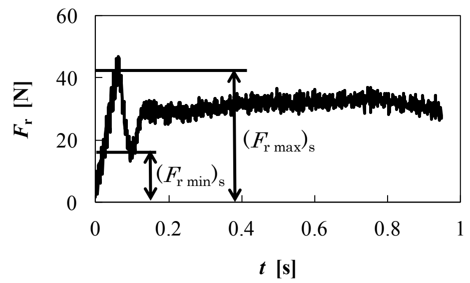
Figure 3 shows a typical example of the measured position, velocity, friction force and acceleration in *z*-direction of the cylinder when a stepwise signal was supplied to the proportional control valves. The position was varied linearly as shown in **Fig.3(a)** and the velocity was varied almost stepwise as shown in **Fig. 3(b)**. **Figure 3(c)** shows the variation of the friction force with time. It is seen from **Fig.3(c)** that the maximum friction force $(F_{r\,max})_s$ appears immediately after the beginning of cylinder operation, that the minimum friction force $(F_{r\,min})_s$ is observed just after the maximum friction force, and that a steady friction force is reached. Friction characteristics similar to **Fig.3(c)** were observed at different stepwise velocities. **Figure 3(d)** shows the variation of the acceleration in *z*-direction with time. The components of the acceleration in *x*, *y* directions are omitted because they were very small compared with *z*-component. It is seen that at the beginning of the cylinder operation, the maximum acceleration $(a_{z\,max})_s$ is generated at the same



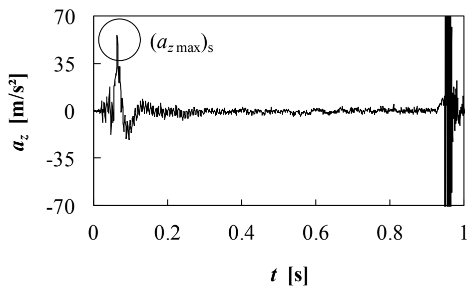
(a) Position



(b) Velocity



(c) Friction force



(d) Acceleration in *z*-direction

Fig. 3 Example of measured values

time the friction force is rapidly decreased from the maximum value to the minimum one. Vibration characteristics similar to **Fig.3(d)** were observed at the other stepwise velocities.

Figure 4 shows the forces acting on the pneumatic piston at the beginning of the piston operation. Until just before the piston starts to move, the static friction force is formed on the contact surfaces of the pneumatic cylinder. As the pressure in the cylinder chamber is increased by the supplied air, the force to push the cylinder increases. When the force to push the piston exceeds the maximum static friction force, the piston begins to move. At the moment, the friction force is suddenly decreased due to the Stribeck effect, i.e., the negative resistance characteristic of friction. Therefore, the piston is rapidly accelerated.

Figure 5 shows the relation between $(F_{r\,max})_s$ -$(F_{r\,min})_s$ and $m\times(a_{z\,max})_s$. The broken line shows the relation of $m\times(a_{z\,max})_s = (F_{r\,max})_s - (F_{r\,min})_s$. It is seen from **Fig.5** that the acceleration is mainly caused by the steep decrease of friction force.

Figure 6 shows a dynamic friction characteristic shown on the friction force - velocity plane and is compared with the steady-state friction characteristic. The steady-state friction characteristic was obtained by plotting the steady values of friction force at different stepwise velocities as shown in **Fig.6(a)**. The dynamic friction force almost traces the steady-state friction characteristic and reaches a steady value, as shown in **Fig.6(b)**. However, when the stepwise velocity is large, the dynamic friction force becomes larger than the steady-state friction force in low-speed region.

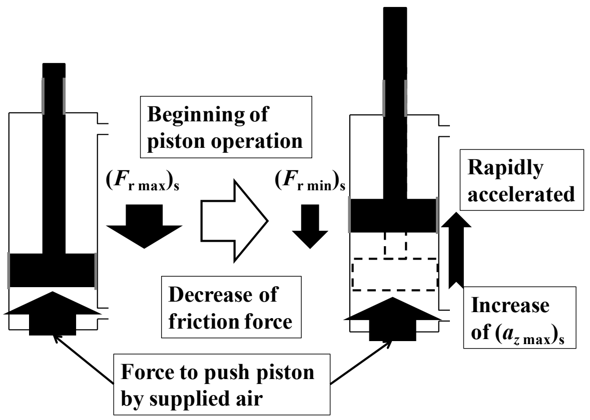


Fig. 4 Forces acting on pneumatic piston at beginning of piston operation.

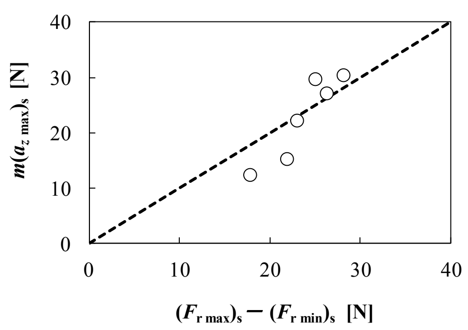
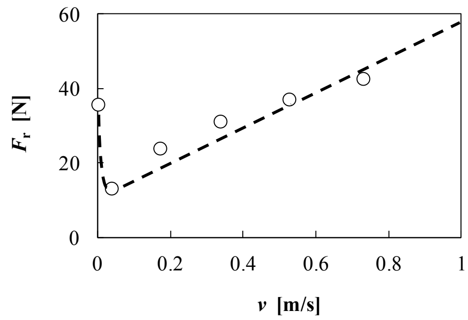
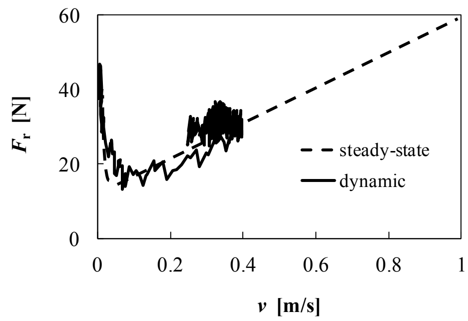


Fig.5 Relation between $(F_{r\,max})_s$ - $(F_{r\,min})_s$ and $m\times(a_{zmax})_s$

3.2 The case for half-period sinusoidal velocity variation

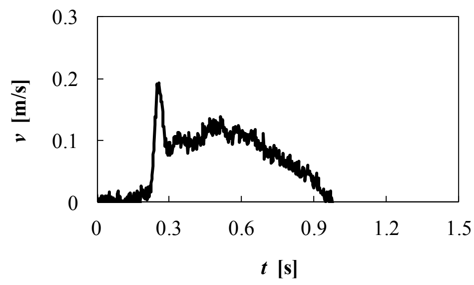


(a) Steady-state friction characteristic

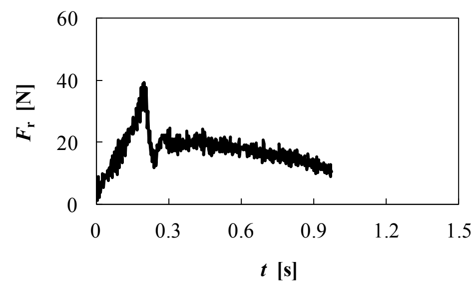


(b) Dynamic friction characteristic

Fig. 6 Dynamic friction behavior – stepwise velocity

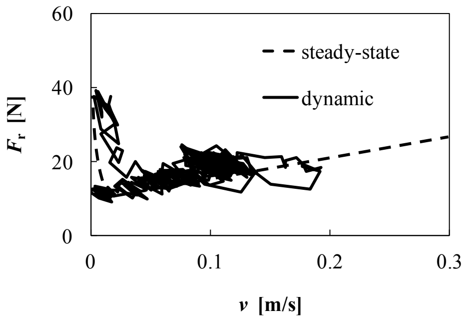


(a) Velocity

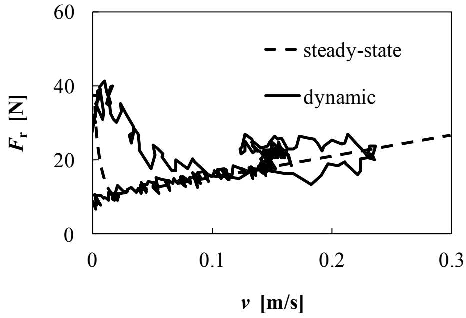


(b) Friction force

Fig. 7 Example of measured half-period sinusoidal velocity and friction force



(a) Frequency = 0.4 Hz



(b) Frequency = 1.0 Hz

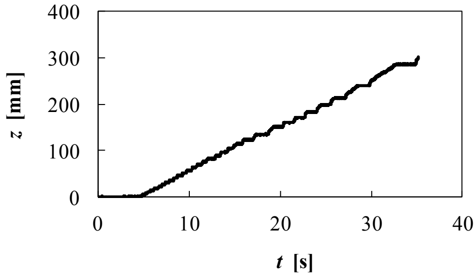
Fig. 8 Dynamic friction behavior – sinusoidal velocity

Figure 7 shows a typical example of the measured velocity and friction force when a half-period sinusoidal signal was supplied to the proportional control valves. The velocity was varied almost sinusoidally except for the overshoot observed at the beginning of the motion as shown in **Fig.7(a)**. **Figure 7(b)** shows the variation of the friction force with time. It is seen from **Fig.7(b)** that the maximum friction force appears immediately after the beginning of cylinder operation and that the minimum friction force is observed just after the maximum friction force.

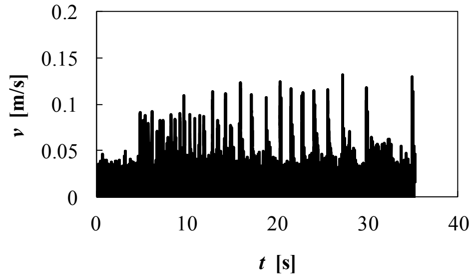
Figure 8 shows the dynamic friction force behaviors at two frequencies of the half-period sinusoidal velocity variation. The dynamic friction force is larger than the steady-state friction force during the acceleration period and traces the steady-state friction characteristic during the deceleration period except for the negative resistance regime. When the frequency of the velocity variation is increased, the size of the hysteresis loop is increased as shown in **Fig.8(a)** and **Fig.8(b)**. These behaviors agree with those reported by Tran et al. [5].

At the mean velocity of 0.010 m/s, a stick-slip motion took place as shown in **Fig. 9**. According to the repeated velocity variations from zero to about 0.1 m/s (**Fig.9(b)**), the friction force is oscillated (**Fig.9(c)**).

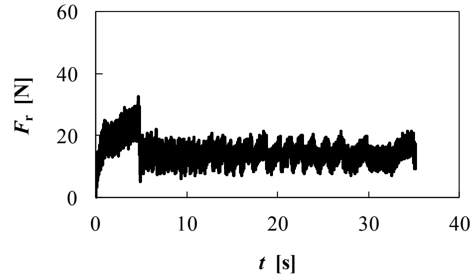
Figure 10 shows the friction force behavior for the case of **Fig.9**. The maximum friction force appears immediately after the beginning of cylinder operation as shown in **Fig.10(a)**. The size of the hysteresis loop during the second cycle shown in **Fig.10(b)** is decreased in comparison with **Fig.10(a)** and the friction force is almost constant.



(a) Position

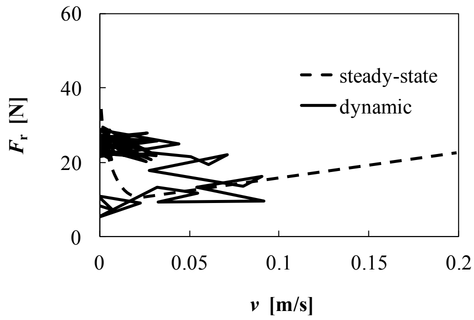


(b) Velocity

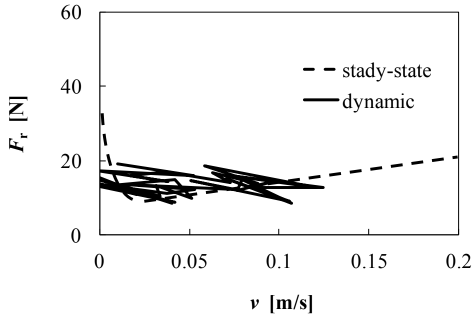


(c) Friction force

Fig. 9 Example of stick-slip behavior

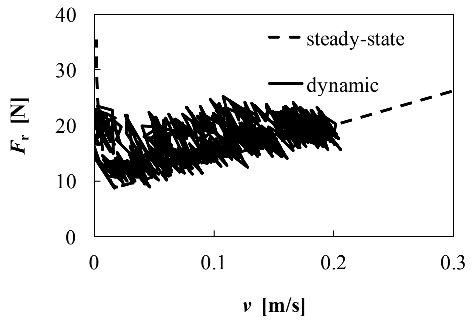


(a) At beginning of cylinder operation

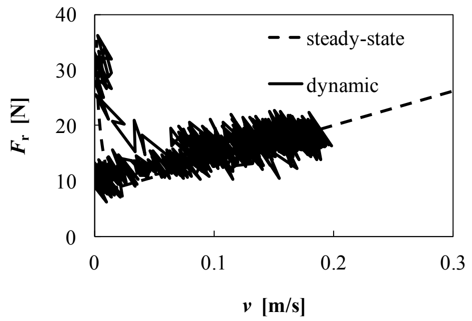


(b) During second cycle

Fig. 10 Dynamic friction behavior in stick-slip motion



(a) Dwell time = 0 [s]



(b) Dwell time = 180 [s]

Fig. 11 Effect of dwell time on dynamic friction behavior

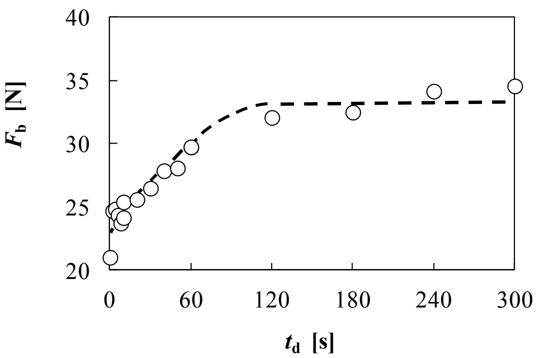


Fig. 12 Effect of dwell time on break-away force

3.3 Effect of dwell time on break-away force

The effect of the dwell time on the dynamic friction characteristic was examined. **Figure 11** shows the dynamic friction force behavior for the dwell time of 0[s] and 180[s]. The break-away force and the shape and size of the hysteresis loop are different between the two dwell times.

Figure 12 shows the effect of the dwell time t_d on the break-away force F_b. It is seen that the break-away force increases with the increase of the dwell time but tends to approach a constant value asymptotically at the dwell time longer than 120 s.

4 Conclusions

The friction and vibration characteristics of a pneumatic cylinder in practical operations were examined under stepwise and half-period sinusoidal velocity variations. It has been shown that a relatively large acceleration is caused at the start of the cylinder motion resulting mainly from a steep decrease in friction force immediately after the start. A frequency-dependent hysteretic behavior during acceleration and deceleration periods as well as a constant friction characteristic in stick-slip motion has been shown. Modeling of the dynamic friction behaviors is the subject for a future study.

5 Acknowledgements

The authors would like to express their gratitude to SMC Corporation for donating pneumatic components used in the investigation.

References

[1] Khayati, K., Bigras, P. and Dessaint, L., “LuGre Model-based Friction Compensation and Positioning Control for a Pneumatic Actuator Using Multi -objective Output-feedback Control via LMI Optimization”, Mechatronics, Vol. 19, (2009), pp.535-547.

[2] Raparelli, T., Manuello, B. A. and Mazzo, L., “Experimental and Numerical Study of Friction in an Elastomeric Seal for Pneumatic Cylinders”, Tribology International, Vol. 30, No. 7, (1997), pp.547-552.

[3] Hamiti, K., Voda, B. A. and Roux, B. H., “Position Control of a Pneumatic Actuator under the Influence of Stiction”, Control Engineering Practice, Vol. 4, No. 8, (1996), pp.1079-1088.

[4] Kosaki, T. and Sano, M., “Chaotic Oscillation Observed in Low Speed Actuation of Pneumatic Cylinders”, Transactions of JSME(C), Vol. 66, No. 648, (2000), pp.2524-2531.

[5] Tran, X. B., Wakasawa, Y. and Yanada, H., Dynamic Friction Behaviors of Pneumatic Actuators, Proceedings of the 4th International Conference on Manufacturing, Machine Design and Tribology, ICMDT 2011, Gamagori, (2011), pp.33-34,

Received on November 30, 2013

Accepted on January 22, 2014