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.
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:

\[
F_r = p_1 A_1 - p_2 A_2 - mg - ma
\]

(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 the \( z \)-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 \( (F_{r_{max}}) \) appears immediately after the beginning of cylinder operation, that the minimum friction force \( (F_{r_{min}}) \) 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 the \( z \)-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 \( \left( a_{z_{max}} \right) \) is generated at the same
time the friction force is rapidly decreased from the maximum value to the minimum one. Vibration characteristics similar to Fig.3(b) 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 \((F_{r \text{ max}}), -(F_{r \text{ min}}),\) and \(m \times (a_{t \text{ max}})^2\). The broken line shows the relation of \(m \times (a_{t \text{ max}})^2 = -(F_{r \text{ max}}) - (F_{r \text{ min}})\). 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.

3.2 The case for half-period sinusoidal velocity variation

![Fig. 7 Example of measured half-period sinusoidal velocity and friction force](image)
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.
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.

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References


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