Dynamic Behaviors of Pneumatic Cylinder
(Friction and Vibration Characteristics)

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An experimental study of the dynamic behaviors of a pneumatic cylinder is presented, and the relation between the friction characteristics and the vibration characteristics is discussed. In the experiments, a pneumatic cylinder is operated in upward or downward motion. The piston velocity was varied to investigate dynamic friction characteristics and their effect on the vibration characteristics. Step input signals or half-period sinusoidal input signals were supplied to flow control valves when measuring dynamic friction characteristics. When the frequency of the sinusoidal signal and the stepwise velocity are increased, the size of the hysteresis loop is increased. A stick-slip motion takes place more easily in upward motion. Finally, the effect of the dwell time on the dynamic friction characteristic is examined. The break-away force increases with the increase of the dwell time, but the dwell time for the break-away force to become the constant value (the maximum static friction force) considerably differs in the operation direction.

Keywords: Friction, Vibration, Pneumatics, Cylinder, Dynamic Characteristics, Nonlinearity, Proportional Control Valve

1. Introduction

This paper presents the dynamic behaviors of a pneumatic cylinder. It is known that the friction force acting on the contacting surfaces between the piston and cylinder wall of a pneumatic cylinder shows a high nonlinearity especially at low velocities. Therefore, accurate positioning of a pneumatic cylinder is not easy.

Many experimental and numerical studies can be found in the relevant literature on the positioning of the pneumatic actuator including the problem of the nonlinear friction1-4). Khayati et al.1) studied the high-friction pneumatic actuator positioning technique based on a LuGre friction closed-loop observer dynamics. They reported that the performances were validated experimentally on a pneumatic plant operating under a high level of friction, and that the robust LuGre model-based friction compensator was experimentally compared to other friction compensation and position control schemes. However, the nonlinear friction characteristics of the pneumatic actuator have not completely been elucidated, and vibration characteristics have not been examined.

This paper shows friction and vibration behaviors of a pneumatic cylinder and the relation between the friction characteristics and the vibration characteristics of the pneumatic cylinder. Moreover, the effect of the dwell time on the break-away force is also examined.

2. Nomenclature

\( A \) : pressure-receiving area
\( a \) : acceleration
\( F \) : force
\( g \) : acceleration of gravity
\( m \) : mass
\( p \) : pressure
\( t \) : time
\( v \) : velocity
\( z \) : position

Subscript

1 : lower cylinder chamber
2 : upper cylinder chamber
\( b \) : break-away
\( d \) : dwell
max : maximum
min : minimum
\( r \) : friction
\( z \) : \( z \) direction

3. Experimental Apparatus and Method

The experimental apparatus is shown in Figure 1. A standard pneumatic cylinder (MDBL32-300, SMC Corporation), 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
(LWH500, Novotechnik Corporation) and two pressure sensors (PSE540A, SMC Corporation) 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 (9G210S, Nippon Avionics Corporation) glued on the cylinder and the metal bar to connect the piston and the potentiometer.

In the experiments, the pneumatic cylinder was operated in upward (extending:+) or downward (retracting:-) motion as shown in Figure 2. The air flow rate supplied to the cylinder was controlled by two proportional flow control valves (VEF3121-2, SMC Corporation). The piston velocity was varied to investigate dynamic friction characteristics and their effect on the vibration characteristics.

When measuring steady-state friction characteristic, step signals with different magnitudes were supplied to the flow control valves. After a certain transient period, a steady-state is reached, and the piston velocity settles into a constant value. During the constant velocity period, friction force reaches a steady-state, i.e., a constant value. Step input signals or half-period sinusoidal input signals were supplied to the flow control valves when measuring dynamic friction characteristics. The piston velocity was obtained by approximately differentiating the position.

The friction force, \(F_r\), was obtained from the equation of motion of the pneumatic piston as follows:

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

### 4. Results and Discussion

#### 4.1 Steady-state Characteristics

The steady-state friction characteristic was obtained by plotting the steady values of friction force at different constant velocities as shown in Fig.3. The positive and negative velocities and friction forces correspond to the extending and retracting strokes, respectively. A Stribeck effect, i.e., a negative resistance characteristic of friction is observed near zero velocity, and the friction force is linearly increased with the velocity except for the vicinity of zero velocity.

#### 4.2 The Case for Half-period Sinusoidal Input Signal

Figure 4 shows a typical example of the measured velocity and friction force in the extending and retracting strokes 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.4 (a). Figure 4 (b) shows the variation of the friction force with time. It is seen from Fig.4(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 5 shows the dynamic friction force behaviors at two frequencies of the half-period sinusoidal signal in the extending and retracting strokes. Broken lines indicate the steady-state friction characteristic. In both strokes, 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 sinusoidal signal is increased, the size of the hysteresis loop is increased as shown in Fig. 5(a) and Fig. 5(b). These behaviors agree with those reported by Tran et al.\textsuperscript{5).}

4.3 The Case for Stepwise Input Signal

Figure 6 shows a typical example of a measured velocity, friction force and acceleration in \(z\)-direction of the cylinder when a stepwise signal was supplied to the proportional control valves in the extending and retracting strokes. The velocity was varied almost stepwise as shown in Fig. 6(a). Figure 6(b) shows the variation of the friction force with time. In both strokes, it is seen from Fig. 6(b) that the maximum friction force \( F_{r \text{ max}} \) appears immediately after the beginning of cylinder operation, that the minimum friction force \( F_{r \text{ min}} \) is observed just after the maximum friction force, and that a steady-state friction force is reached after that. Friction characteristics similar to Fig. 6(b) were observed at different stepwise velocities. Figure 6(c) 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. In both strokes, it is seen that at the beginning of the cylinder operation, the maximum acceleration $a_{z_{\text{max}}}$ 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.6(c) were observed at the other stepwise velocities.

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. Therefore, the piston is rapidly accelerated.

It may be considered that such a relatively large acceleration is caused by the sudden decrease in friction force. Figure 7 shows the relation between $F_{r_{\text{max}}} - F_{r_{\text{min}}}$ and $ma_{z_{\text{max}}}$ in both strokes. The broken line shows the relation of $ma_{z_{\text{max}}} = F_{r_{\text{max}}} - F_{r_{\text{min}}}$. It is seen from Fig.7 that $ma_{z_{\text{max}}}$, i.e., $a_{z_{\text{max}}}$ is not necessarily increased with the increase of $F_{r_{\text{max}}} - F_{r_{\text{min}}}$. In stepwise input signal, when the stepwise velocity is increased, $F_{r_{\text{max}}}, F_{r_{\text{min}}}$ and $a_{z_{\text{max}}}$ is increased. However, $F_{r_{\text{max}}} - F_{r_{\text{min}}}$ is decreased with the increase of the stepwise velocity. Therefore, $ma_{z_{\text{max}}}$ is decreased with the increase of $F_{r_{\text{max}}} - F_{r_{\text{min}}}$ as shown in Fig.7.

Figure 8 shows a dynamic friction characteristic shown on the friction force - velocity plane when the piston velocity was varied stepwise from rest to a positive velocity or to a negative one and is compared with the steady-state friction characteristic. The dynamic friction force dose not almost trace the steady-state friction characteristic and reaches a steady value, as shown in Fig.8. When the stepwise velocity is large, the dynamic friction force becomes larger than the steady-state friction force.

At the mean velocity of 0.010 m/s in the extending stroke and -0.017 m/s in the retracting one, 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)). In the experiments, the stick-
slip motion was easy to take place in the extending stroke as shown in Fig.9.

Figure 10 shows the friction force-velocity behaviors for the case of Fig.9. The dynamic friction behavior during the first cycle of the stick-slip motion is shown in Fig.10(a), and that during the second cycle is shown in Fig.10(b). The size of the hysteresis loop during the second cycle (a stable limit cycle) shown in Fig.10(b) is much smaller than that observed during the first cycle shown in Fig.10(a), and the friction force is almost constant during the second cycle. The maximum friction force in Fig.10(b) is smaller than the one in Fig.10(a) because the dwell time of piston is short, as discussed in the next section.

4.4 Effect of Dwell Time on Break-away Force

Figure 11 shows the dynamic friction force behavior for the dwell time of 0 s and 300 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 $F_b$ in the extending and retracting strokes. 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 and 240 s, respectively.

5. Conclusion

Dynamic friction characteristics and vibration characteristics of a pneumatic cylinder were examined under various velocity variations. The relation between the vibration characteristic and the dynamic friction characteristic at the start of the cylinder motion was also
examined. A frequency-dependent hysteretic behavior during acceleration and deceleration periods as well as a constant friction force characteristic in stick-slip motion were shown. The effect of the dwell time on the break-away force in the extending and retracting strokes were made clear. Modeling of the dynamic friction behaviors is the subject for a future study.

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References