VIETNAM ACADEMY OF SCIENCE AND TECHNOLOGY

Vietnam Journal of MECHANICS

Volume 36 Number 4

ISSN 0866-7136

VN INDEX 12.666

4

2014

Vietnam Journal of Mechanics, VAST, Vol. 36, No. 4 (2014), pp. 283 – 290

EXPERIMENTAL INVESTIGATION OF FRICTION BEHAVIOR IN PRE-SLIDING REGIME FOR PNEUMATIC CYLINDER

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Received July 17, 2014

Abstract. Friction always presents in pneumatic cylinders and causes difficulties in controlling position and velocity of pneumatic systems. In order to improve the control performace of the pneumatic systems, it is necessary to fully understand behavior of friction in the pneumatic cylinders. So far, dynamic friction behavior of pneumatic cylinders has been investigated but mainly focused on the friction behavior in sliding regime. In pre-sliding regime, friction behavior has not been investigated. In this paper, experimental investigations of friction behavior of a pneumatic cylinder in pre-sliding regime are made. The friction force is calculated from the equation of motion of the piston using the measured values of pressures in the two cylinder chambers and the piston displacement. The pressures are controlled by using two proportional pressure control valve. The friction force versus piston displacement characteristics are measured and analysed under various operating conditions of the applied force and the pressures. Experimental results show that: i) the piston motion in pre-sliding regime exhibits a nonlinear spring behavior; ii) hysteretic behavior with nonlocal memory is verified; iii) the pressures have influence only on the size of the hysteretic loop. These experimental results can be applied to develop a friction model for pneumatic cylinders.

Keywords: Pneumatic cylinder, friction behavior, pre-sliding regime, hysteresis behavior, nonlocal memory.

1. INTRODUCTION

Pneumatic cylinders are often used in industrial applications for reasons related to their good power/weight ratio, easy maintenance and assembly operations, clean operating conditions and low cost. However, friction always exists in the pneumatic cylinders and causes difficulties in controlling the position and velocity of the pneumatic systems, especially in applications with high precision positioning and with low velocity tracking. It is, therefore, necessary to understand fully friction behavior in pneumatic cylinders in order to improve the control performace of the pneumatic systems.

Several experimental methods have been proposed to investigate the friction behavior of the pneumatic cylinders. Schoroeder and Singh [1] proposed an experimental test setup in which the friction force was calculated by detecting the force exchanged by the rods of the tested pneumatic cylinder and of a load pneumatic cylinder assembled with a reversed working direction. Belforte et al. [2] proposed an experimental test setup in which the velocity of the test pneumatic cylinder was controlled by a driving hydraulic cylinder and the pressures of the chambers were controlled by proportional pressure control valves in order to measure the friction force under a broad range of operating conditions of velocity and pressures. Andrighetto et al. [3] proposed an experimental test apparatus to examine the friction behavior for pneumatic cylinders with different sizes and types. The above experimental studies have focused on investigating the friction behavior of pneumatic cylinders in steady-state conditions and have shown that the steady-state friction force-velocity characteristics of the pneumatic cylinders are represented by Stribeck curves.

Tran and Yanada [4] have proposed a test setup to study friction behavior of pneumatic cylinders in dynamic conditions. They have shown that when the piston velocity varies sinusoidally without velocity reversals, the dynamic friction force-velocity characteristic exhibits a hysteretic behavior (frictional lag) around the steady-state friction characteristic at low velocities. In addition, they have shown that the hysteretic loop is expanded to higher velocities when the frequency of the velocity variation is increased, and its size increases with the driving pressure and decreases with the resistance pressure.

It is well known in mechanical system that [5] friction may be present in two regimes: *sliding regime* in which the friction force depends on the velocity, and *pre-sliding regime* in which the friction force depends on the asperity displacement. As written above, the friction behavior of the pneumatic cylinders has been investigated but only in sliding regime. In pre-sliding regime, friction behavior of pneumatic cylinders has not been made clearly. In this paper, a test setup is made to investigate the friction behavior of a pneumatic cylinder in pre-sliding regime. The friction force versus piston displacement characteristics are measured and discussed under different operating conditions of applied force and supply pressure, i.e. pressures in the two cylinder chambers.

This paper is organized as follows: Section 2 describes the test setup and experiments. Experimental results are presented and discussed in Section 3. Finally, conclusion is given in Section 4.

2. EXPERIMENTAL TEST SET-UP

The experimental test setup used in this investigation is shown in Fig. 1. In this test set-up a pneumatic cylinder with its piston diameter, piston rod diameter and stroke of 25 mm, 10 mm and 300 mm, respecively, was used. The motion of the cylinder piston was controlled by providing the pressures p_1 and p_2 into the two cylinder chambers. The pressures in the two chambers of the pneumatic cylinder were independently controlled by using two proportional pressure control valves. The valves provide air flow up to 0.025 m^3/s and allow controlling the pressures up to 1 MPa.

A displacement sensor with a measured range of 2 mm and with an accuracy of 0.04% F.S was used to measure the displacement of the piston. In order to sense the signal of the piston displacement to the sensor, a circular object made of iron was connected to the piston head. Two pressure sensors with an accuracy less than 2% F.S. were used to measure the pressures, p_1 and p_2, in the cylinder chambers.

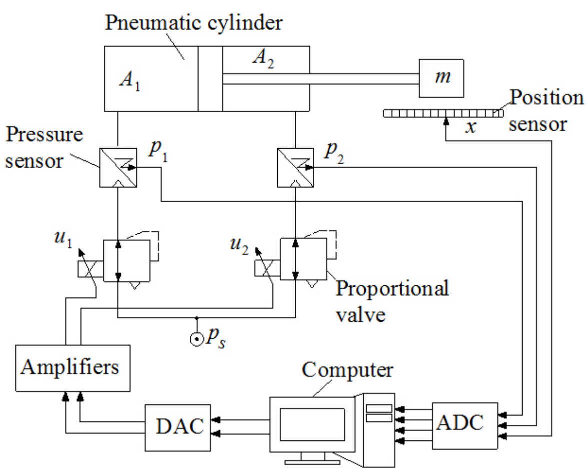

Fig. 1. Schematic of experimental test set-up

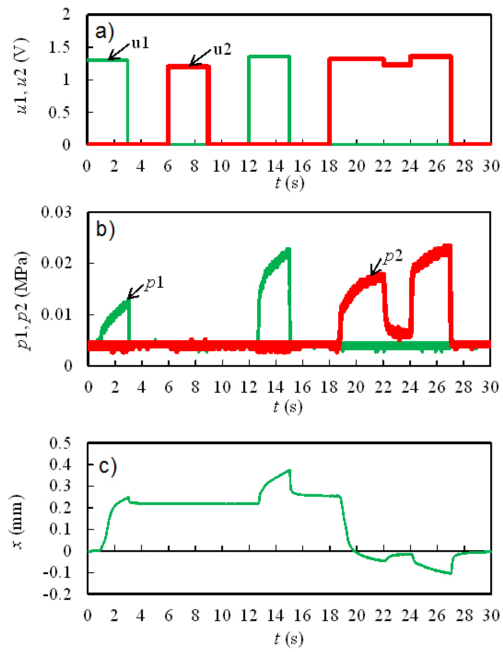

Fig. 2. Example of experimental data at $p_s = 0.4$ Mpa: a) valve inputs, b) pressures, c) piston displacement

The signals of pressures and displacement from the sensors were read into a computer through an A/D converter and the computer provided the control signals, u_1 and u_2, to the proportional valves through a D/A converter. Experimental data, i.e., pressures, p_1 and p_2, and displacement of the piston, x, were recorded at the interval of 1 ms. An example of the measured data is shown in Fig. 2. Details of the devices used in the test setup are shown in Tab. 1.

Table 1. Name, maker and mark of devices used in experimental test set-up

Name of devices	**Makers**	**Marks**
Pneumatic cylinder	SMC	CM2L25-300Z
Proportional valves	SMC	VEP3121-1-02
Valve amplifiers	SMC	VEA250
Pressure sensors	SMC	PSE540
ADC/DAC	Advantech	USB-4711A
Position sensor	Panasonic	GP-A10M

The friction force, F_r, is obtained from the equation of motion of the pneumatic piston using the measured values of the pressures in the cylinder chambers and the inertia force as follows

$$F_r = p_1 A_1 - p_2 A_2 - ma, \tag{1}$$

where A_1, A_2 are the piston areas; m is the total mass of the piston, piston rod and the sensing object; a is the acceleration of the piston. The friction force was measured in the pre-sliding regime, i.e., the regime that the velocity equals nearly zero and, therefore, the term of the inertia force in Eq. (1) was ignored.

The aim of this investigation is to investigate the friction force versus displacement characteristics under different conditions of the applied force and the supply pressure, i.e., different conditions of the pressures in the cylinder chambers. In order to vary pressures in the two cylinder chambers, different current signals were supplied to the proportional pressure control valves and the supply pressure, p_s, was varied from 0.1 to 0.6 Mpa. All the experiments were conducted at Laboratory of Fluid Power and Automation Engineering, School of Transportation Engineering, Hanoi University of Science and Technology.

3. RESULTS AND DISCUSSION

Fig. 3 shows the friction force versus displacement characteristics under three values of the applied force at a constant supply pressure of 0.4 MPa in the extending stroke of the cylinder.

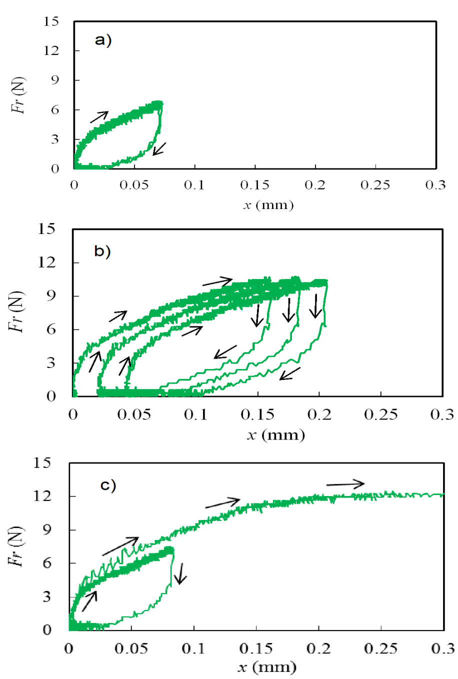

Fig. 3. Friction force-displacement characteristics under different applied forces in extending stroke of the piston at $p_s = 0.4$ Mpa

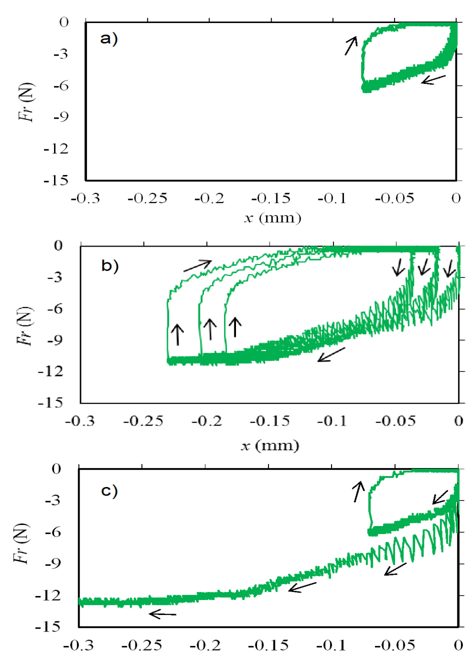

Fig. 4. Friction force-displacement characteristics under different applied forces in retracting stroke of the piston at $p_s = 0.4$ Mpa

In Fig. 3a, when the applied force is ramped up to a certain value that is less than the break-away force, the piston takes elastical deformation. When the applied force is removed, i.e. set the applied force equal zero, the piston will return to the original position but following a new curve. Essentially, the piston deformation is caused by deformation of the asperity junction between the piston/rod seals and the cylinder walls.

In Fig. 3b, when the applied force is ramped up to a higher value than that in Fig. 3a, the asperity junctions deform elastically then plastically. When the applied force is removed, the asperity junctions does not return back to its original position but will be a new position at the distance that equal to the plastic deformation of the asperity junctions from its original location. When the force is re-applied and then removed, the same behavior can be obtained.

In Fig. 3c, when the applied force is ramped up to a value greater or equal to the level of the break-away friction force, the asperity junctions will break and a true sliding occurs.

The small loop in Fig. 3c is identical to the loop in Fig. 3a. The same behavior shown in Fig. 3 can be also observed in Fig. 4 for the retracting case of the cylinder piston. The behavior observed in Figs. 3 and 4 verifies that the piston motion in pre-sliding exhibits nonlinear spring behavior and they are similar to those observed in other mechanisms [6,7].

Fig. 5 shows a friction force versus displacement characteristic when the applied force is ramped up to a value smaller than the breakaway friction in the extending stroke direction then removed, and the same force is ramped up again in the opposite direction, then removed. The result is shown in Fig. 5 with a hysteretic loop behavior. Both elastic and plastic deformation of the asperity junction can be found in the hysteretic loop.

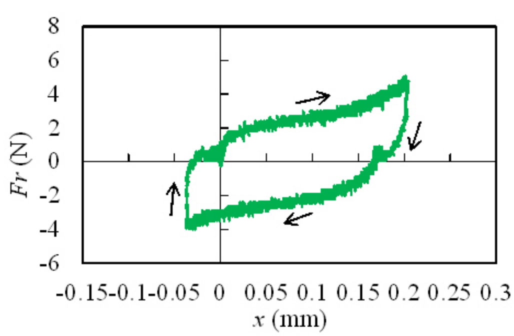

Fig. 5. Friction force-displacement characteristic when the force is applied in both the extending and retracting strokes

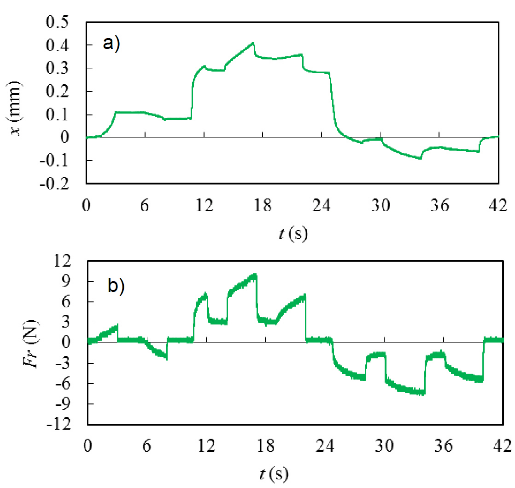

Fig. 6. The piston motion trajectory and the corresponding friction force with several velocity reversal points per period: a) piston displacement, b) friction force

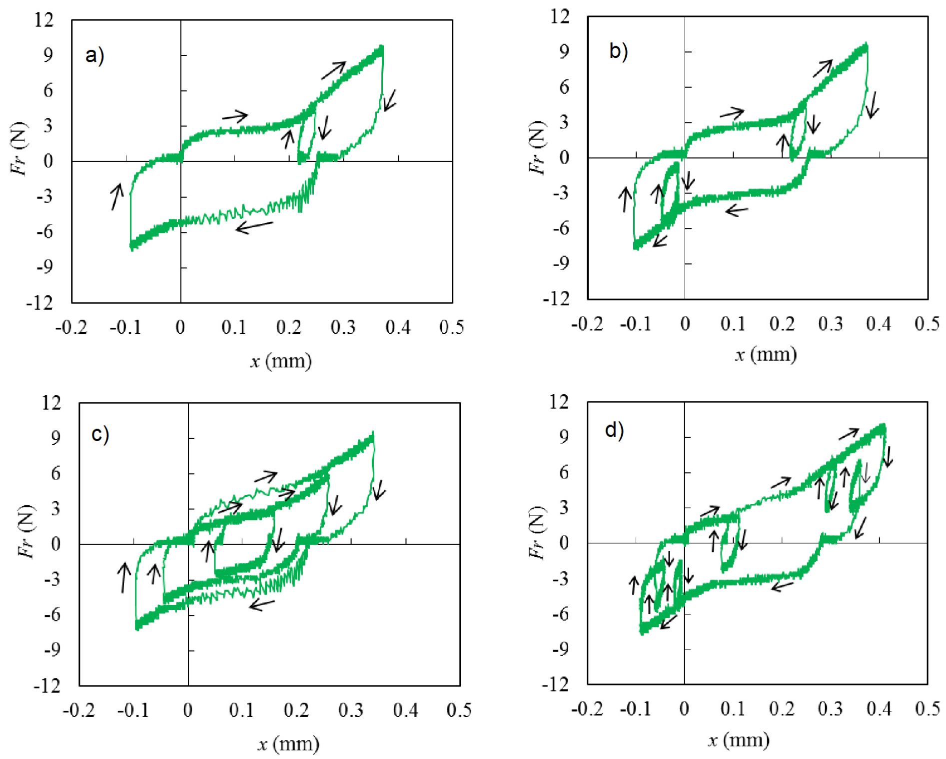

Fig. 7. Measured hysteretic loop behavior with nonlocal memory in pre-sliding regime

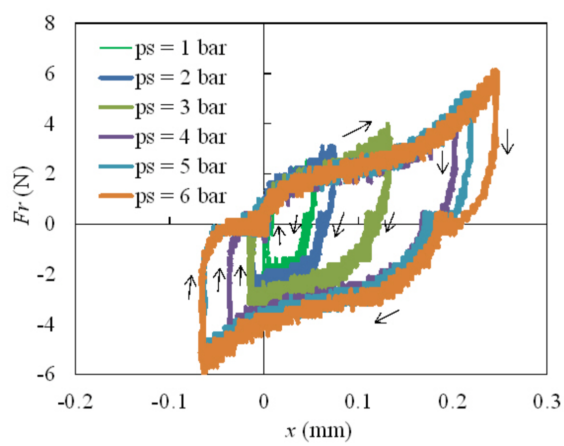

Fig. 8. Friction force-displacement characteristics under different supply pressures

When a piston motion is varied with several velocity reversal points per period, within the pre-sliding region, an example of such a motion is shown in Fig. 6 together with the friction force, and when the two sets of measured synchronized data are plotted against each other, an external loop is obtained with one or several internal loops within it, see Fig. 7. This hysteretic behavior is called *hysteresis with nonlocal memory* [8]. This kind of hysteresis means that the future values of the function friction force in this case at some instant of time t ($t > t_0$) depend not only on its present value at the instant of time t_0 and the value of its argument displacement in this case but also on the past extremum values of the function. This property is in contrast to the behavior of *hysteresis with local memory*, where the past has its influence upon the future through the current value of the function.

Fig. 8 shows the friction force-displacement characteristics measured under different values of the supply pressures from 1 bar to 6 bar. The smallest loop is corresponded to the supply pressure of 1 bar and the largest loop is corresponded to the supply pressure of 6 bar. As can be seen from Fig. 8, the size of the hysteretic loop increases with increasing the supply pressure. However, shape of the hysteretic loop is not affected by the supply pressure.

4. CONCLUSIONS

In this paper, the friction behavior of a pneumatic cylinder in pre-sliding regime was investigated. The friction force versus displacement characteristics were measured and analysed under the operating different conditions of the applied force and the supply pressure. The results shows the following behavior: i) the piston motion in pre-sliding regime exhibits a nonlinear spring behavior; ii) hysterstic behavior with nonlocal memory is verified; iii) the pressures have influence on the size of the hysteretic loop. These experimental results can be applied to develop a friction model for pneumatic cylinders in future research.

ACKNOWLEDGMENTS

This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 107.01-2012.15.

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