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Measurement of frictional force characteristics of pneumatic cylinders under dry and lubricated conditions

***Abstract**. This study developed a novel measurement system for the friction force characteristics of pneumatic cylinders. The dynamic characteristics of pneumatic cylinder are affected by guide seal, piston seal, grease and surface of cylinder bore. In seeking to improve the friction force characteristics of pneumatic cylinders and to clarify the friction phenomenon of the pneumatic cylinders, this study describes friction force measurement tests to measure the friction force of pneumatic cylinder, under both dry and lubricated conditions. Experimental equipments are designed to assess the effect of seals and lubrications in pneumatic cylinder, where the velocity and pressure of the driving cylinder are controlled. Measurements of friction force are shown for velocities of up to 200 mm/s. This paper provides an easy and accurate measurement system to analyze the friction characteristic of pneumatic cylinder. The data obtained will be useful for developing a suitable friction model, and the experimental apparatus will facilitate the study of the effects of different types of seals and lubricants on friction force.*

***Streszczenie.** W artykule zaproponowano nowy system pomiarowy do analizy siły tarcia w cylindrach pneumatycznych. Celem jest poprawa charakterystyk tarcia i dlatego badania przeprowadzono w warunkach suchych i mokrych przy kontrolowanych szybkości i ciśnieniu. (**Pomiary siły tarcia w cylindrach pneumatycznych w warunkach suchych i mokrych**)*

Keywords: friction force; pneumatic cylinder; seal; grease.
Słowa kluczowe: siła tarcia, cylinder pneumatyczny.

1. Introduction

The important role of pneumatic systems in factory automation can be seen in many industrial devices, but, with the evolution of industrial automation, speed and reliability, the characteristics of low friction and long life-time are required more and more often for all pneumatic actuators. Better knowledge of the frictional characteristics of seals for pneumatic actuators will improve the description of cylinder motion, optimize the effective force of the cylinder, and prevent stick-slip action, thus, allowing cylinders to achieve smoother motion, and improved positional accuracy and bandwidth in pneumatic servo systems. Moreover, such knowledge can help to optimize seals and establish better procedures for preventive maintenance [1]. To reach these goals, a fuller knowledge and description of the characteristics of each single pneumatic component are critical. However, few studies have been done on the frictional characteristics of the seals for pneumatic actuators. A deep knowledge of the frictional characteristics at the rubber–metal interface is required, since highly effective low friction seals must be available to optimize system performance and avoid excessive wear in industrial applications.

A number of experimental and numerical studies have aimed at analyzing the frictional characteristics between seals and their counter faces. Raparelli et al. [2] experimentally validated a numerical approach to evaluate seal performance, under actual working conditions. Sui et al. [3] developed an experimental procedure to better predict seal behavior in field operations, long-term measurements of friction and wear rate under lubricated conditions with different rotating speeds and different contact pressure. Belforte et al. [4] designed an experimental apparatus that allows the measurement of friction forces in cylinders of different sizes and for a broad range of velocities and pressures of both cylinder chambers. Ghathian et al. proposed an approach to develop a mathematical relationship for determining the friction force in O-ring sealing elements resulting from deformation between the working surfaces [5]. Andrighetto et al. [6] analyzed the friction characteristics of several tested pneumatic actuators from many different manufacturers through their main friction coefficients obtained from experimental friction-velocity maps. Gawlinski et al. The friction measurement results are shown as a function of velocity and pressure. The experimental apparatus will be useful for studying the influence of other parameters, such as the piston seal, cylinder bore, and lubricant-related characteristics, on the friction force.

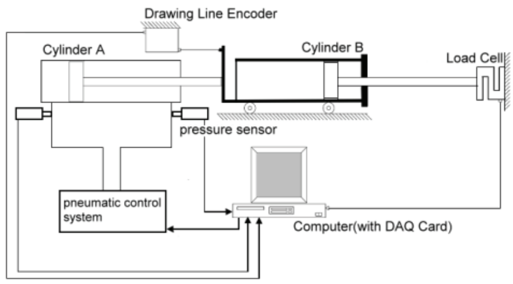

Fig. 1. Schematic view of the experimental apparatus

2. Experimental characterization

2.1 Test set-up

The test setup, schematically represented in Fig 1, simulates the behaviour of a friction system of pneumatic cylinder consisting of a guide seal, a piston and seal sliding inside a cylinder bore. It consists of the pneumatic cylinders being tested and their respective valves and sensors. Four sensors were set up to measure the position, velocity, and pressure of both chambers of the pneumatic cylinder, as well as the force. Three variables, the rod velocity and the pressures of both chambers of the pneumatic cylinder, were controlled and kept constant. In this test system, the motion of pneumatic cylinder (B) is driven by the action of the pneumatic cylinder (A) independent of the pressure difference at its chambers. The pressure of the air compressor unit is set at 10 kPa, providing enough force to actuate a pneumatic cylinder (B). On the right, a load cell was fixed on the wall and connected with the rod of the pneumatic cylinder (B) to measure the friction force between the seals and the cylinder bore of the pneumatic cylinder (B). Three sensors were set up to measure the position, velocity, and pressure of both chambers of pneumatic cylinder (A). In the test, three variables, the rod velocity and the pressures of both chambers of pneumatic cylinder (A), were controlled and kept constant by the throttle valves and pressure regulator valves. The guide seal, piston seal and the bore of the pneumatic cylinder (B) were tested under dry and greased conditions.

2.2 Piston seals

The seals being tested was mounted on the front cover(1) and the cylinder piston (2), and placed inside the cylinder bore (3) as shown in Figure 2. In the experiments, the seals were tested under dry and greased conditions. In the lubricating tests, the grease CPC LB80102 was filled in the groove (4) of the piston. This paper also discusses the effect of the grease applied in the sealing system.

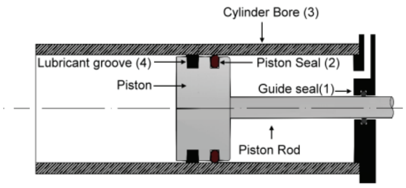

Fig. 2. Piston seal setting

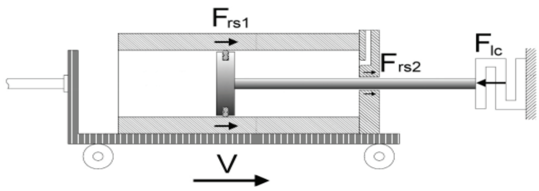

Fig. 3. Friction Forces acting in the tested cylinder

The actual value of the friction force between the piston and the cylinder is affected by the seal characteristics and size, by the relative velocity. The forces acting on the moving assembly when the bore is displaced by the pneumatic cylinder are shown in Figure 3. From the equation of the dynamic balance of the tested cylinder moving at a constant speed, we have:

$$F_{rs1} + F_{rs2} - F_{lc} = 0 \quad (1)$$

where F_{lc} is the force at the load cell, F_{rs1} are the friction forces at the seals of the piston, and F_{rs2} is the friction force at the seal of the rod cover. In this study, the measurement system aims to precisely measure the friction force between the seals on the piston and the cylinder bore. Therefore, the back cover of the tested cylinder was removed to avoid the effects of the pressure in the rear chambers. The new design can precisely measure the friction force of the seal in the pneumatic cylinder by the load cell.

2.3 Test procedure

Motion is caused by the force exerted by the driving pneumatic cylinder. The test measured each seal under both dry and lubricated conditions. Each test included two processes – the extended process and retracted process. In accordance with the role played by pressure during the effective cylinder operation, the chamber which empties during the motion was defined as the resistance chamber, and the other one was defined as the driving chamber. In the extended process, the driving pressure was set to 6kPa and the relative pressure at the resistance (front) chamber was raised to 7 kPa before the pneumatic cylinder (a) was started. Before the retracted process was started, the relative pressure at the resistance (rear) chamber was kept at 6 kPa and the driving pressure was set to 6kPa to drive the pneumatic cylinder (a). The operation settings of pressure in both chambers make the motion of the pneumatic cylinder stable.

3. Results and discussion

3.1 Static Friction Force

Figure 4 shows the distribution of the static friction forces along the cylinder. Results are shown for extended motion of the piston at 3, 5, 8, 10, 15, 25, 35, 50, 100, and 200mm/s. It can be seen from Figure 4 how the static friction force of the seals is distributed under different velocity settings and lubricating conditions. Comparing the friction force for each seal when the A-PSD seal was tested under the dry condition, the friction force was raised at low velocity (under 50mm/s). The highest static friction force of the A-PSD seal under a dry condition was attained at 133N. High static friction force made the pneumatic system spend more time overcoming the static friction force to force the piston to move. In this case, the performance of the A-APA seal was better than that of the A-PSD seal in static friction force distribution under both dry and lubricated conditions. The results show that the lower operation velocity occurred higher friction force because the lubricating film is hard to be formed in lower operation velocity of piston and the APA-50 have better self-lubricated ability than A-PSD.

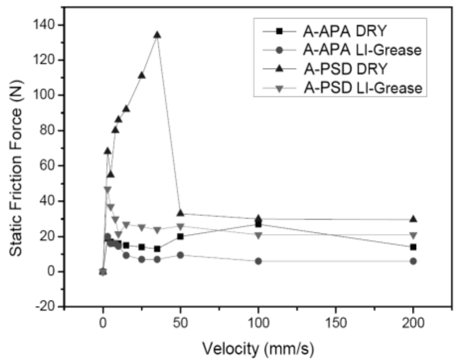

Fig. 4. Static friction force versus velocity

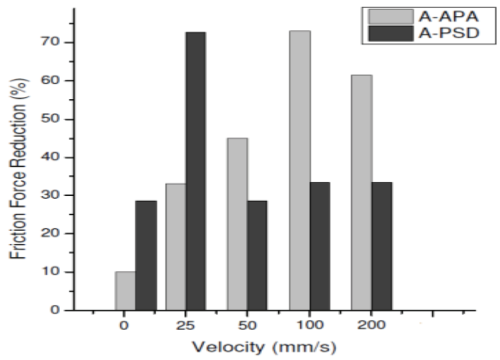

Fig. 5. Static friction force reduction by Li-grease

In Figure 5, the Li-grease can efficiently reduce the friction force of A-APA in higher velocity operation. The reduction of Li-grease for A-APA was over 60%. In the other hand, the highest friction force of A-PSD was occurred in 25mm/s. After the Li-grease was employed, the friction force reduction was 72.7%. The effect of Li-grease can be observed by this new friction force measurement system. The reduction of static friction force can decrease the delay time of initial motion of the pneumatic cylinder.

3.2 Dynamic Friction Force

Figure 6 shows the distribution of the average dynamic friction forces along the cylinder. In Figure 6, it can be seen that the dynamic friction forces of the A-PSD seal under a dry condition increased from 5mm/s to 35mm/s. When the velocity was over 50mm/s, the dynamic friction force of the

A-PSD seal was decreased and became stable. Moreover, the dynamic friction force of the seals under the lubricated condition was obviously smaller than that under the dry condition.

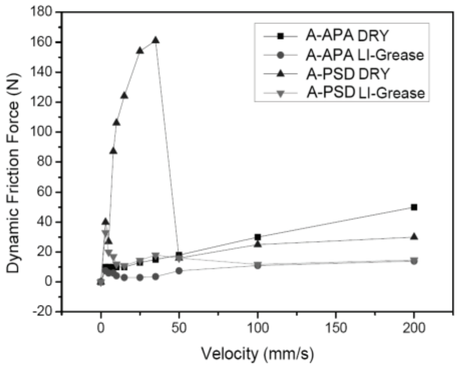

Fig. 6. Dynamic friction force versus velocity

The dynamic friction forces were higher in lower operation velocity because the rubbing area between piston seal and cylinder bore is larger. When the operation velocity is getting higher, the friction force will be suddenly decreased to a minimum value and then the friction forces will be increase slowly. We compared the measured dynamic friction force curves of the experiment equipment with Stribeck curve, the results of this study can be reasonable.

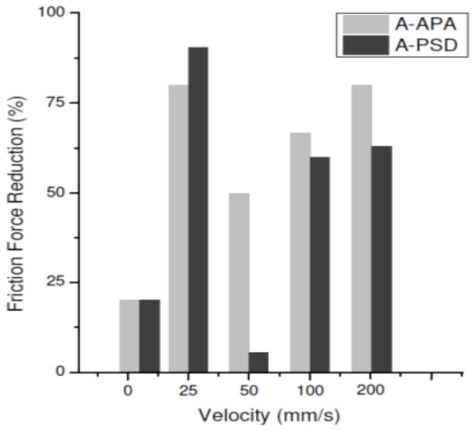

Fig. 7. Dynamic friction force reduction by Li-grease

In the Figure 7, it can be seen that the dynamic friction force reduction was evident, and it can decrease the waste of power of the pneumatic cylinder. Comparison with static friction force, the Li-grease is more efficient to decrease the dynamic friction force. The dynamic friction characteristics can be analyzed by this pneumatic cylinder friction force measurement system.

3.3 Dynamic Friction Force characteristic

In this study, the friction force measurement system is developed to analyze the friction force characteristic. The stick-slip phenomenon was observed in Figure 8a. The dynamic friction characteristic of A-PSD in 5mm/s was unstable. When the Li-grease was lubricated in the seal system, the dynamic friction characteristic was improved (Figure 8b). In low operation velocity, the stick-slip phenomenon was easily to affect the positioning accuracy of the pneumatic cylinder.

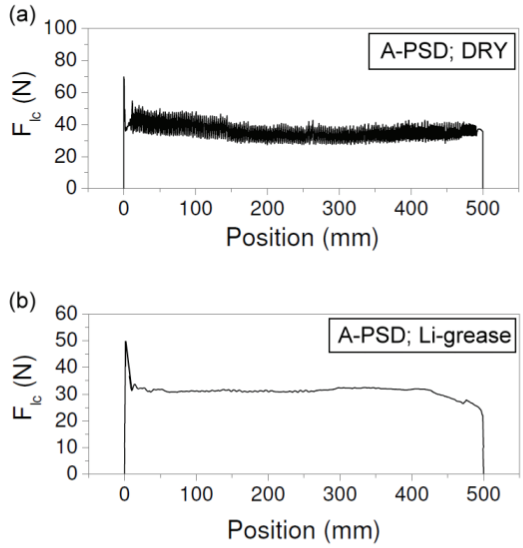

Fig. 8. Friction force characteristic of A-PSD at 5mm/s, (a) DRY; (b) Li-grease

In Figure 9a, when the operation velocity was raised, the dynamic characteristic of the piston motion is getting to become smooth. After the Li-grease was employed at 50mm/s, the friction force was decreased obviously, and the difference between static friction force and dynamic friction force was reduced, shown in (Figure 9b). The reduction of the difference between static friction force and dynamic friction force can make the stability of the positioning of the pneumatic cylinder.

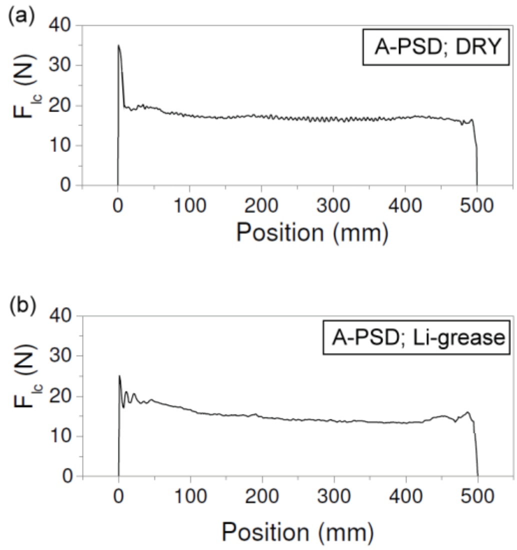

Fig. 9. Friction force characteristic of A-PSD at 50mm/s, (a) DRY; (b) Li-grease

In the high operation velocity condition, the dynamic characteristic of piston motion was stable. In the Figure 10, it can be seen that the function of Li-grease in the operation velocity condition is decreasing the friction forces of the pneumatic cylinder. In lubricating condition, the power consumption was smaller because of the reduction of the friction force of the pneumatic cylinder.

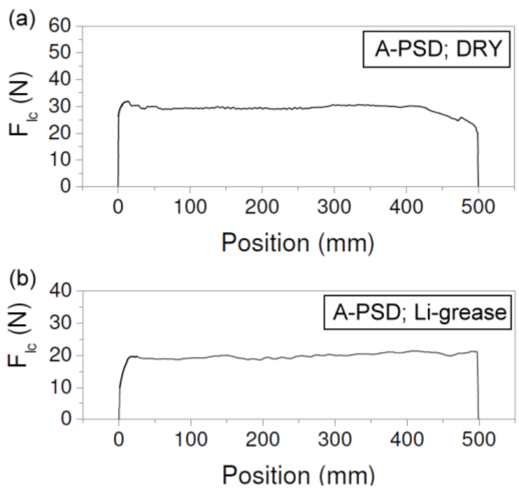

Fig. 10. Friction force characteristic of A-PSD at 200mm/s, (a) DRY; (b) Li-grease

Conclusions

In this study, we developed a friction force measurement system. We describe an experimental apparatus to measure the friction force of seals in pneumatic cylinders. The experimental apparatus allows for the measurement of friction forces in cylinders of different seals and for a broad range of velocities of pneumatic cylinders. Two seals were tested under both dry condition and lubricated conditions. The results show that the friction force varies according to piston motion under different velocity operations. From the measurement tests, the friction characteristics and their relationships with velocity are experimentally clarified.

According to the results, the friction forces of seals were significantly reduced by lubricated grease. The results show that the dynamic characteristic of A-APA under the dry condition was the steadiest at 5mm/s, and the dynamic characteristic of A-PSD under the lubricated condition was the steadiest at 200mm/s. The A-APA has better self-lubricating ability and great frictional properties. This friction force measurement system can be used to analyze the frictional properties of seals in pneumatic cylinder. The dynamic characteristics can be obtained by the results of the friction force characteristic analysis. The results provide the engineer a reference to design and test the new pneumatic cylinder system.

Acknowledgments

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