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Simulation and Investigation of Factors Affecting the Internal Friction Force of Pneumatic Cylinders

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Extended Abstract

Introduction

Pneumatic systems are widely used in industrial and agricultural applications, particularly in industrial automation, because of their simple structure, relatively low installation cost, high reliability, safety, rapid operation, and considerable flexibility. Pneumatic actuators convert the energy stored in compressed air into mechanical motion and are commonly classified into linear cylinders, continuous rotary actuators, and limited-angle rotary actuators. Among these, pneumatic cylinders are extensively employed for producing reciprocating linear motion. Despite their advantages, the compressibility of air may cause non-uniform motion of the moving member, which can limit the accuracy of pneumatic actuators in precision applications. Therefore, improving the dynamic characteristics of pneumatic cylinders is essential for achieving accurate and stable motion. Among the parameters affecting the performance of pneumatic cylinders, the frictional force between the piston seals and the internal cylinder wall has a significant influence on piston motion and power transmission. Friction affects the acceleration, velocity, positioning accuracy, and smoothness of the moving member. Accurate determination of the friction force is particularly difficult at high piston velocities and accelerations because the friction force is not constant during the piston stroke and is affected by several interacting parameters. These parameters include the output load, air pressure on both sides of the piston, piston velocity, acceleration, flow resistance, lubrication conditions, and the properties of the sealing material. Consequently, relying only on the nominal characteristics of the seal or lubricant may not provide an accurate estimation of the actual frictional behavior of the cylinder. In the present study, a method for determining the internal friction force of pneumatic cylinders is proposed and evaluated. A double-acting pneumatic cylinder is investigated experimentally and numerically, and the effects of piston velocity, pressure on both sides of the piston, and piston dwell time on the internal friction force are examined. The proposed method is based on measuring the pressures acting on both sides of the piston and its acceleration, and subsequently determining the friction force from the dynamic force balance of the piston.

2. Materials and Methods

A double-acting pneumatic cylinder was selected for the investigation. The cylinder has a **piston diameter of 32 mm** and a **stroke length of 150 mm**. To investigate the dynamic behavior of the cylinder, the relationship between inlet pressure, load, velocity, and acceleration was simulated using **Sim Fluid** software. The simulation considered the forward movement of the piston following actuation of the directional control valve. During the forward stroke, compressed air is supplied to one side of the piston while air from the opposite annular chamber is discharged toward the atmosphere. Immediately after switching the directional control valve, the generated pneumatic force may remain lower than the total resisting force, and therefore the piston does not initially move. When the driving force becomes greater than the resisting force, piston motion begins and acceleration occurs. As the piston accelerates, the pressure conditions on the two sides of the piston change, gradually reducing the acceleration until the driving and resisting forces become balanced and the piston approaches a constant velocity. During the cushioning stage, restriction of the exhaust flow increases the back pressure and consequently reduces the piston acceleration. The associated compression and flow processes can also influence the air temperature and the frictional behavior of the system. The pneumatic circuit was designed according to the **out-meter flow-control method**, in which the exhaust flow is controlled to regulate the velocity of the actuator. This configuration generates back pressure on the opposite side of the moving member and can partially compensate for load fluctuations. Flow control was achieved using flow-control and check valves, allowing the piston velocity to be controlled during both forward and return strokes. For experimental determination of the friction force, two **5/3-way solenoid directional control valves** were used to control the supply and exhaust of compressed air from the two cylinder chambers. A control unit was employed to actuate the solenoid valves. The experimental setup was equipped with an **acceleration sensor** for measuring the acceleration of the piston or attached moving member, a **position sensor** for determining the piston position, and **pressure sensors** for measuring the air pressures in the two cylinder chambers. The friction force was determined using the dynamic force balance of the piston. In this formulation, P1P_1 and P2P_2 represent the air pressures acting on the full and annular sides of the piston, respectively, while A1A_1 and A2A_2 represent the corresponding piston areas. The other parameters include the mass of the moving load mm, acceleration aa, friction force FRF_R, and external load resistance FLF_L. To eliminate the influence of an externally applied load and obtain a more direct measurement of the internal friction, the experiment was performed without applying an external load to the cylinder rod. Therefore, after measuring P1P_1, P2P_2, and the piston acceleration, the internal friction force could be calculated from the corresponding dynamic force equation. Finally, the outputs of the pressure, acceleration, and position sensors were processed to obtain the relationship between the internal friction force and the linear velocity of the moving member. This procedure makes it possible to evaluate friction throughout the piston stroke and under different dynamic operating conditions.

3. Results and Discussion

The results obtained for the pneumatic cylinder with a **32 mm piston diameter and 150 mm stroke** demonstrated that the friction force is strongly dependent on the dynamic state of the piston and cannot be described solely by the properties of the sealing material or lubricant. Immediately after switching the directional control valve, the piston does not begin moving instantaneously. During this initial period, which is associated with the response time of the pneumatic circuit, the friction force increases sharply. This behavior is attributed to the static friction between the piston seals and the inner wall of the cylinder. In the stationary condition, the friction coefficient is higher than that associated with the moving condition, and consequently a relatively high driving force is required to overcome the initial resistance and initiate piston motion. Once the piston begins to move, the friction force decreases because the friction coefficient between the moving seals and the cylinder wall is lower than that in the stationary condition. This behavior is characteristic of the transition from static to dynamic friction. Therefore, the experimental friction–velocity response does not simply increase monotonically from the beginning of motion. Instead, an initial friction peak is followed by a reduction after the onset of motion. With further increasing piston velocity, the friction force begins to increase again, although with a lower slope than the initial increase. According to the study, this second increase is associated with changes in the volume of pressurized air, partial interruption or deceleration of piston motion, changes in the friction coefficient, and variations in pressure on the two sides of the moving member. Thus, the frictional behavior is governed by an interaction between mechanical contact phenomena and pneumatic operating conditions. The results clearly indicate that **piston velocity, pressure on both sides of the piston, and piston dwell time** are important factors affecting the internal friction force. Consequently, a friction model based only on seal material and lubricant characteristics would not adequately represent the actual behavior of a pneumatic cylinder under dynamic operating conditions. The experimental approach adopted in this study provides a direct means of capturing these dynamic effects and can therefore be useful for improving the modeling and control of pneumatic servo systems. An important advantage of the proposed measurement approach is that it does not require complicated force-measuring equipment directly attached to the piston. Instead, the friction force is determined from measurable pneumatic pressures and piston acceleration using the force balance. This makes the method relatively simple and economical while maintaining the ability to characterize friction during actual cylinder operation. The proposed approach can also

be applied to single-acting and double-acting cylinders as well as rodless pneumatic cylinders. Furthermore, it allows the friction force to be determined at different piston velocities and at different positions along the cylinder stroke.

4. Conclusions

In this study, a practical method was proposed for determining the internal friction force between the piston seals and the inner wall of pneumatic cylinders. The method combines measurements of the air pressure on both sides of the piston with measurements of piston acceleration and position, allowing the friction force to be obtained from the dynamic force balance of the pneumatic cylinder. The method was evaluated for a double-acting pneumatic cylinder with a **32 mm piston diameter and 150 mm stroke**. The experimental results demonstrated that internal friction is influenced not only by the seal material and lubricant but also by the **piston velocity, air pressure on both sides of the piston, and piston dwell time**. A significant increase in friction was observed before the piston started moving, corresponding to the static friction required to initiate motion. After motion began, the friction decreased due to the transition from static to dynamic friction and subsequently increased again as piston velocity and pneumatic operating conditions changed. The proposed method offers several advantages, including **short measurement time, low cost, simple experimental configuration, high accuracy, the possibility of measuring friction during actual actuator operation, applicability to single-acting, double-acting, and rodless cylinders, and the ability to determine friction at different velocities and positions along the piston stroke**. Therefore, the method can provide useful information for modeling, design, and control of pneumatic actuators, particularly in applications requiring smooth motion, high positioning accuracy, and reliable dynamic performance.

Keywords: Pneumatics, Double-Acting Cylinder, Friction Force, Velocity.

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