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An Experiments and Characteristics Analysis of the Sealless Cylinder

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ABSTRACT

: This paper shows a performance analysis for conical type sealless cylinders and rod bearings. The pistons without seal have partly cylindrical and conical shapes. 2 dimensional Reynolds equation and FD(finite differential) numerical techniques are utilized for the performance analysis. The relationship among self-centering forces and leakage flows are investigated. Also, optimal design values for a sealless cylinder are presented. A prototype of sealless cylinder which had rod bearing with four pockets, five pockets, and six pockets was manufactured respectively. Leakage flow test is conducted to evaluate performance of piston and rod bearing in sealless cylinder.

KEY WORDS

Sealless Piston, Pneumatic Cylinder, Reynolds Equation, Self-Centering Force, Leakage Flow

NOMENCLATURE

Q_1, Q_2, Q_3: Supply flow
Q_A, Q_B, Q_C: Leakage flow
h_1, h_2: Membrane thickness
c_1, c_2: Clearance between piston and cylinder
p_s: Internal pressure
p_a: Atmosphere pressure
L: Length of piston
ϵ: Eccentricity
$\dot{m}$: Leakage flow

1. INTRODUCTION

Because the general cylinders use sliding seal, it causes the high friction force and adherence phenomenon when it operates in low speed, and the use of the cylinders is not proper in the clean room and high temperature and high pressure environment.

Accordingly, in this study, sealless cylinder attaching conical-type piston without seal is proposed to complement the handicap. This technology can be widely applied to servo actuator responding highly speedy and precise linear movement.

Fig. 1 shows the basic structure of the sealless cylinder. Piston A is composed of two parts of conical portion and cylindrical portion, and it has symmetry structure based on outlet groove in middle area. When the pressure is applied to inside of cylinder, self-centering

force happens, which becomes stronger when the piston moves to left and right sides reciprocally. Therefore, it has a function of composition bearing in which both static pressure effect and dynamic pressure effect act together. Part B is static gas pressure-supporting rod bearing, and Part C has the same function as plane seal.
The following correlation can be drawn from flow conservation law.

$$Q_1 + Q_2 + Q_3 = Q_A + Q_B + Q_C \tag{1}$$

Sealless cylinder was originally proposed by Guido Belforte[1][2], he predicted the performance by deriving the approximate solution of 1D Reynolds equation for the non-moving cylinder.
On the contrary, in this study, 2D Reynolds equation for reciprocal moving sealless cylinder was derived and the solutions were obtained by finite difference method, and then the optimized design conditions were proposed by performing the performance analysis of piston and rod bearing. Finally, feasibility of the design is verified by measuring the leakage flow after manufacturing of the test products.

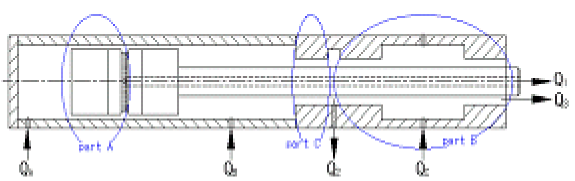
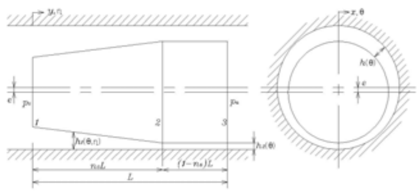
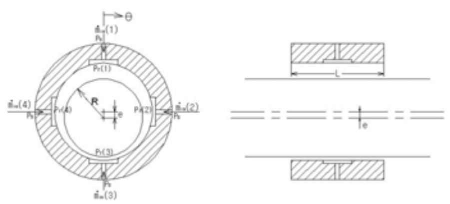


Figure1 Sealless pneumatic cylinder



(a) Conical type piston



(b) Rod bearing

Figure2 Geometry of the sealless cylinders

2. THEORY ON PERFORMANCE ANALYSIS

2.1 Performance analysis of piston

For performance analysis of sealless cylinder, conical type piston and rod bearing type are proposed as seen in Fig. 2(a),(b). Piston is composed of conical portion and cylindrical portion, high pressure, p_s, are acted on the side (face 1) and atmospheric pressure, p_a, are acted on the opposite side(face 3)
The thickness of air layer between piston and cylinder is as follows.

$$h_1 = c_1 + e\cos\Theta \quad (0 \le y < n_s L) \tag{2}$$

$$h_2 = c_2 + e\cos\Theta \quad (n_s L \le y \le L) \tag{3}$$

Where, c_1 and c_2 represent the gaps at each position in radial direction. If $c_2 = c$ is assumed, the following equation can be drawn.

$$c_1 = c + s - \frac{s}{n_s L} y \tag{4}$$

The governing equation for the piston can be expressed as dimensionless Reynolds equation derived by assuming the constant temperature process in air layer.

$$\frac{\partial}{\partial\theta}\left(PH^3 \frac{\partial p}{\partial\theta}\right) + \Gamma \frac{\partial}{\partial\eta}\left(PH^3 \frac{\partial p}{\partial\eta}\right) = \Lambda \frac{\partial}{\partial\eta}(PH) \tag{5}$$

The dimensionless variables are as follows.

$$x = R\theta \tag{6}$$

$$y = L\eta \tag{7}$$

$$p = p_a P \tag{8}$$

$$\Gamma = \frac{R^2}{L^2} \tag{9}$$

$$\Lambda = \frac{6\mu R^2 U}{p_a c^2 L} \tag{10}$$

When eccentric ratio is defined as follow,

$$\varepsilon = \frac{e}{c} \tag{11}$$

The thickness of air layer can be expressed as dimensionless forms.

$$H_1 = \frac{c_1}{c_2} + \varepsilon \cos\theta \tag{12}$$

$$H_2 = 1 + \varepsilon \cos\theta \tag{13}$$

The boundary conditions are as follows.

$$P_{\eta=o} = P_S$$

$$P_{\eta=1} = 1 \tag{14}$$

$$P_{\theta=o} = P_{\theta=2\pi}$$

The leakage flow can be calculated as follow.

$$\dot{m} = \int_0^{2\pi R} \delta x \frac{p_a}{2p_a} p \left(Uh - \frac{h^3}{6\mu} \frac{\delta p}{\delta y} \right) \tag{15}$$

2.2 Performance analysis of rod bearing

Rod bearing is a kind of gas static pressure bearing. Piston rod reciprocally moves in axial direction, the rod is supported by using constant pressure. When high pressure, p_s, is supplied through orifice, constant pressure, p_r, is maintained, which supports the piston rod.
The thickness of air layer between rod bearing and rod is as follow.

$$h = c + e\cos\theta \tag{16}$$

The governing equation for rod bearing is the same as equation (4).The thickness of air layer can be expressed as dimensionless forms.

$$H = 1 + \varepsilon \cos\theta \tag{17}$$

The boundary conditions are as follows.

$$P_{\eta=O} = P_{\eta=1} = 1$$
$$P_{\theta=0} = P_{\theta=2\pi} \tag{18}$$

The leakage flow can be calculated as follows.

$$\dot{m}_\theta = -\int_0^{2\pi R} \delta x \frac{p_a}{2p_a} p \frac{h^3}{6\mu} \frac{\delta p}{\delta y} \tag{19}$$

$$\dot{m}_\eta = \int_0^{2\pi R} \delta x \frac{p_a}{2p_a} p \left(Uh - \frac{h^3}{6\mu} \frac{\delta p}{\delta y} \right) \tag{20}$$

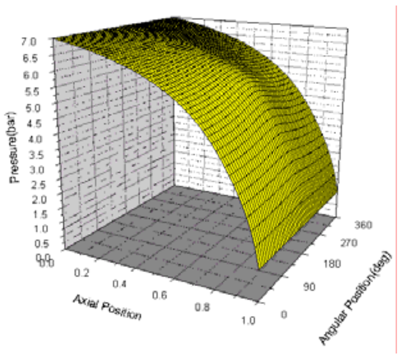
3. RESULT OF PERFORMANCE ANALYSIS

3.1 Calculation of pressure distribution

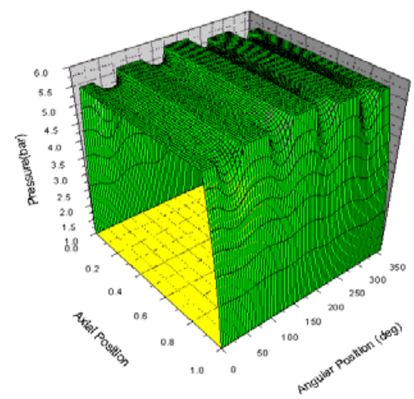
Fig. 3 is a calculating result of pressure distribution at , $\varepsilon = 0.5$, $n_s = 0.8$, $p_s = 7bar$. It can be predicted in the figure that self-centering force at the center region occurs due to pressure difference at $\theta = 0$ and $\theta = 180$.

3.2 Effect of eccentric ratio on performance

Fig. 4(a) and (b) show centering force and leakage flow against eccentricity variation of conical piston and rod bearing at $n_s = 0.8$. The centering force and leakage flow increase as eccentricity increases. It can be seen from Fig. 4(c) that the optimized values occur at ε =0.7 for both conical piston and rod bearing by plotting the load/leakage value to maximize the centering force and to minimize the leakage flow.

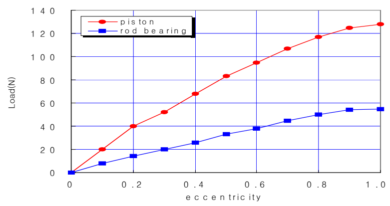


(a) conical piston (ϵ =0.5,ϴ =0.8)

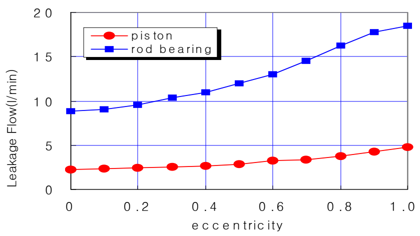


(b) rod bearing (ϵ =0.5)

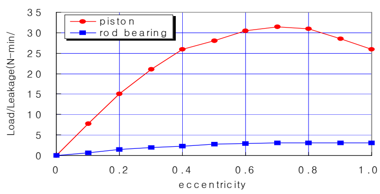
Figure3 Pressure distribution



(a) Load



(b) Leakage



(c) load/leakage

Figure4 Eccentricity vs. performance curve

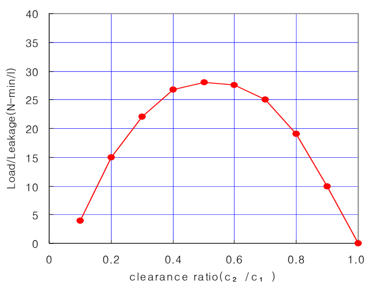


Figure5 Piston clearance ratio vs. performance curve

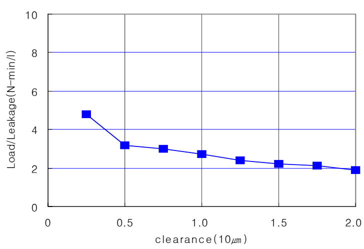


Figure6 Rod bearing clearance vs. performance curve

Table1. Dimensions of Sealless Cylinder

Contents	Length
Cylinder Diameter	50mm
Stroke	500mm
Total Piston Length	208mm
Cylindrical Piston Length	18mm
Conical Piston Length	82mm
Clearance	10μm
Tapered Length	20μm

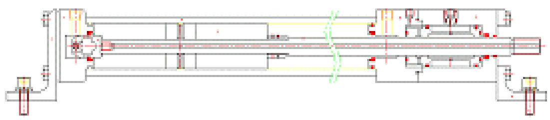


Figure7 Drawing of Sealless Cylinder

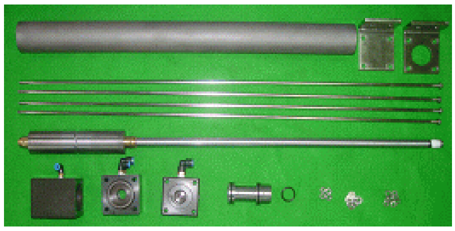


Figure8 Prototype of Sealless Cylinder

3.3 Clearance ratio and effect of clearance on the performance

Fig. 5 and Fig. 6 represent the variation of the load/leakage value against piston clearance ratio and rod bearing clearance to maximize the centering force and to minimize the leakage flow. In case of piston, the optimized value occurs when clearance ratio is 0.5, and in case of rod bearing, the clearance should be small.
It is recommended in real design to determine the satisfactory clearance after fixing the maximum leakage flow.

4. OPTIMIZED DESIGN AND MANUFACTURING OF TEST PRODUCT

Sealless cylinder with optimized conditions based on analysis results was designed and manufactured. The design specification of the sealless cylinder is as Table 1[3].
Fig. 7 is a drawing of the sealless cylinder, and Fig. 8 is a prototype of piston and rod bearing of manufactured sealless cylinder. Fig. 9 represents the type of rod bearing.

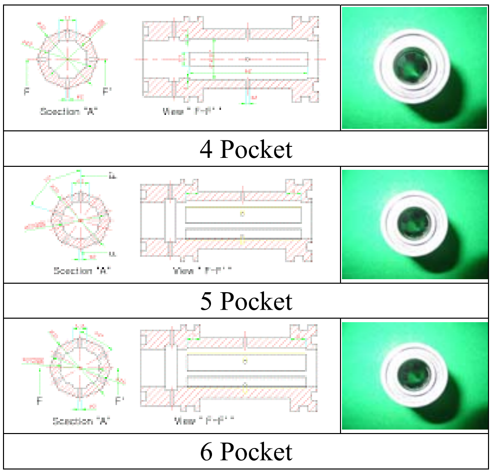


Figure9 Rod Bearing (4, 5, 6 Pockets)

5. LEAKAGE FLOW AND OVERALL PERFORMANCE EXPERIMENTS

5.1 A schematic of experimental apparatus and pictures

The experimental apparatus for overall performance evaluation was composed as Fig. 10. The compressed air is controlled by servo valve, load cell was attached to measure the friction force, position and velocity sensor, LVDT, was also attached, the sensors to measure pressure and flow rate was attached.

An air tank provides the cylinder through a FRL unit with Air. The equipped sensors can measure pressure and flux and the supplied Air can be controlled from servo valve. Also Load Cell and LVDT can measure friction, velocity and displacement at the edge of the cylinder. The acquired signals through sensors can be analyzed from PC.

Fig. 11 is a picture of controller part and mechanism part of the experimental apparatus for overall performance evaluation.

5.2 Experimental results

Fig. 12 is a result for reproducibility confirmation of servo actuator by input of triangle wave to servo valve. The Experiment was performed with a variation of controlling voltage from 5V to -5V under the condition of Pa=1 ㎫ and Q=250ℓ/min. It is confirmed through two experiments that the time when maximum controlling voltage, 5V, occurs is identical.

Fig. 13 is a result for reproducibility confirmation of servo actuator by input of rectangular wave to servo valve like above experiment. As a result, the reproducibility of servo actuator was confirmed. Fig. 14 shows a result of dynamic characteristics of Gain/Phase/Hz by using sine wave.

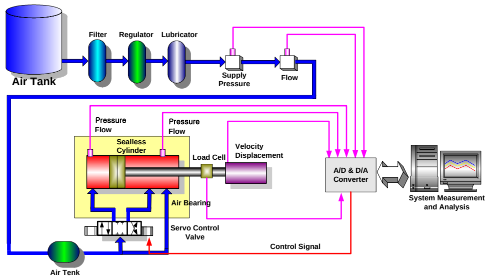


Figure10 Performance Experimental Apparatus

Figure11 Measurement Apparatus of Performance Tester Apparatus

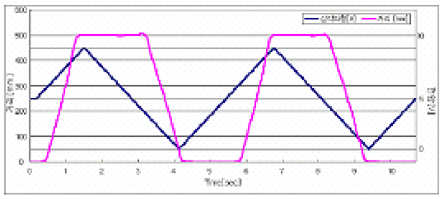


Figure12 Repeating test using triangle wave

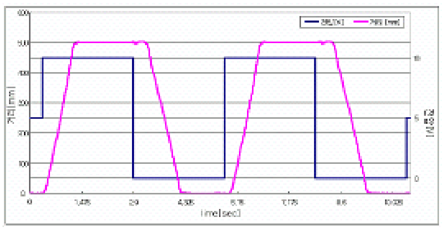


Figure13 Repeating test using rectangular wave

Fig 15 shows a measuring value of leakage flow of piston. Internal pressure was kept at 6 bars and it represents leakage flow at each position due to variation of stroke. At the initial stage, leakage flow is high, but it becomes lower as the piston operates. Finally, the difference of leakage flow is twice.

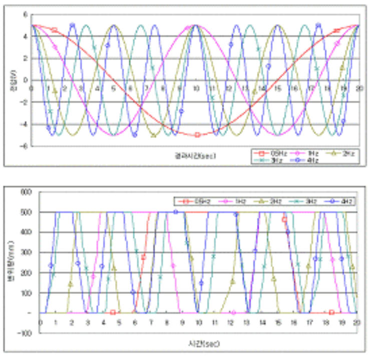


Figure14 Repeating test of Gain/phase/Hz using sign wave

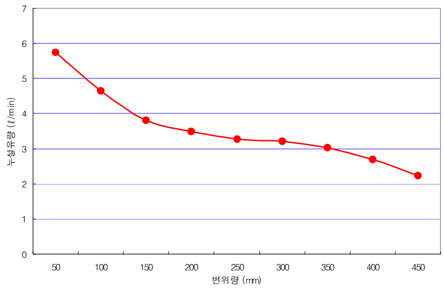


Fig. 15 Leakage flow of piston

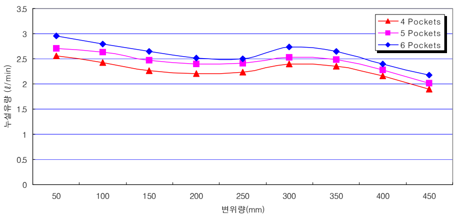


Fig. 16 Leakage flow of rod bearing

It was confirmed that precise manufacturing is excellent, judging from the fact of the leakage flow was evaluated to be approximately 2～6ℓ /min which agrees with theoretical analysis result. Fig. 16 shows a measured leakage flow of rod bearing.
The experiments using 4, 5, and 6 pocket bearing were performed. Internal pressure was kept at 6 bars and it represents leakage flow at each position due to variation of stroke. 4 pocket bearing has the smallest leakage flow, 2.5 ℓ /min, which seems to be caused that the clearance was smelly fabricated compared with theoretical analytic value.

6. CONCLUSION

In this study, following conclusions were drawn from the results of the reproducibility of each wave shape, the dynamic characteristics experiments, and measured leakage flow, varying the piston shape and rod bearing shape of sealless cylinder.

1. High performance sealless cylinder was manufactured by analyzing theoretically the bearing load and leakage flow.
2. Analysis on the conical type sealless cylinder was performed, 2D Reynolds equation on sealless cylinder moving reciprocally were derived, and then the solutions were obtained by finite difference method. It was confirmed that the results were applicable to the design.
3. From the experimental results through manufacturing of sealless cylinder, it was confirmed that 4 pocket bearing has the smallest leakage flow.
4. As the results of the leakage flow measuring, leakage flow of piston was evaluated to be approximately 2 ～ 6ℓ/min, which agrees with theoretical analysis results. Rod bearing shows the leakage flow of 2.5 ℓ/min, which seems to be caused that the clearance was smally fabricated compared with theoretical analytic value.

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