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Development of the Pneumatic Rotary Actuator for Marine Winch

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Abstract : It is well known that pneumatic actuators convert fluid power into mechanical power with a low efficiency. The pneumatic rotary actuators are used in not only marine winches, but also hoists, agitators, and excavators. The efficiency of pneumatic rotary actuators depends on several factors, such as type of actuator, speed, supply pressure, size and geometry of the actuator. This paper presents an analytical and experimental study of the performance of pneumatic rotary actuators. We investigate all the major aspects of the air flow through a pneumatic rotary actuator and points out the main causes of the low efficiency of the actuator. Therefore the design parameters which can lead to optimum performance are obtained

Key words : Pneumatic Rotary Actuator, Optimum Performance, Efficiency

1. Introduction

A pneumatic motor is an actuator to convert fluid power into continuous rotary motion by using the compressed air by an air compressor as a working fluid, and it has been used instead of an electric motor in a place where inflammable gas exists, such as a mine, a chemical factory, a ship and so on. Recently, its demand is on the rise, including its demand for tools, a conveyor, a hoist, an agitator, general industrial machines, and the like.

The pneumatic rotary actuator, on which this study was conducted, means a motor having vanes installed in a rotor and further revolving by the compressed air flowing between vanes. It has a small or medium capacity that its power is 7.5 kW or less and its rpm is 15,000 or below. In case its rpm is 500 or below, it seeks to secure high torque and stability in a low speed domain by installing a reducer therein.

The pneumatic rotary actuator is classified into a non-expanding type and an incomplete expanding type. In the case of the incomplete expanding type motor, a primary exhaust port is formed in the middle of the vane to use the expansion energy of the compressed air,

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and thus, its efficiency is relatively high. On the other hand, in the case of the non-expanding type motor, its air consumption is great and its efficiency is low, but it has an advantage that it can be miniaturized because its volumetric power is great.

So far, many studies have been conducted on a pneumatic rotary actuator; for example, Jacazio[1] et al. conducted a study on optimization of performance of a rotary actuator; PU[2] et al. conducted a study on the servo control technology using a pneumatic motor; Perry[3] reported the result of a study applying a new concept to the design of a non-expanding type vane pump.

In this study, as characteristics of performance of a non-expanding type pneumatic rotary actuator having the specifications of 4 HP, 2,500 rpm, 7.5 nm and 8 vanes, power, torque and flow variation were measured and identified by respective rpm's. And, after installing a worm gear reducer having a reduction ratio of 20:1 therein, such characteristics were measured by using a full automatic tester. In order to control the supply pressure and the supply flow rate accurately, a servo valve was used, and for a load section, an air dynamometer was adopted. And, the number of acquiring data per 1 channel was made to be 2,300 per second so that the accuracy of data was sought.

2. Theoretical background

Fig.1 is a schematic view of the structure of the rotary actuator on which this study was conducted. It has theoretical characteristics as follows.

That is to say, the vane is completely absorbed into the inside of the rotor at Point Q, and the vane is expanded 100% at Point Z. The maximum diameter of the rotor is greater than 2/3 of the diameter of the motor.

$$r > \frac{2}{3}B \tag{1}$$

Also, the maximum working area of the rotary actuator is as expressed by the following expression.

$$S = L(x-1) \tag{2}$$

wherein, L is the axis directional expanded length of the vane, r is the diameter of the rotor, and x is the geometric value of physical property.

$$x = (B^2 - e^2 \sin^2\phi)^{\frac{1}{2}} + e\cos\phi \tag{3}$$

From Expression (3), it can be known that in the case of B+e, x has the maximum value, and in the case of $\phi = 0$, the vane is positioned on the line of QZ.

In Fig. 1 and 2, each control volume of the driving section and the exhaust chamber is as follows.

$$\begin{aligned} V_a &= V_0 + \int_0^{\phi} \frac{L}{2x^2} B d\phi \\ V_b &= V_0 - \int_0^{\phi} \frac{L}{2x^2} B d\phi \end{aligned} \tag{4}$$

wherein, $V_0 = \frac{\pi}{2} L(B^2 - r^2)$

The minimum value of the inactive area is as follows.

$$-\frac{\phi m}{2} < \phi < +\frac{\phi m}{2} \tag{5}$$

wherein,

$$\phi m = \frac{2\pi}{n} \tag{6}$$

In Expression (3), if ϕm or ϕ is regarded as 0(zero), that is to say, when the number of rotary actuators is maximum,

$$x = B + e \tag{7}$$

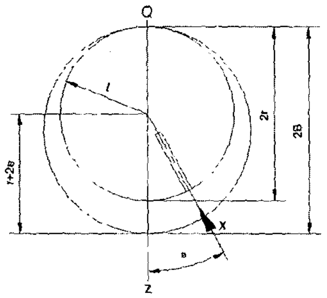

Fig. 1 Simplified rotary actuator structure.

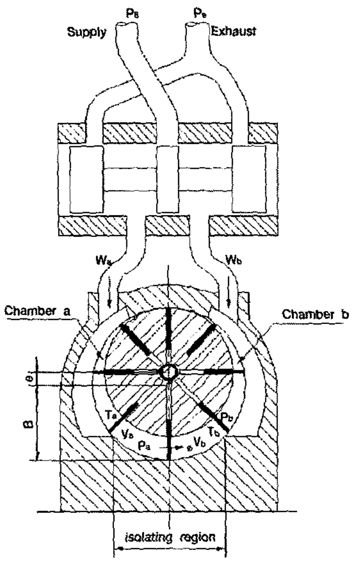

Fig. 2 Rotary actuator controlled by a servo valve.

Accordingly, each control volume of the inlet and the outlet of the rotary actuator is as follows.

$$V_a = V_0 + 2eBL\phi \tag{8}$$

$$V_b = V_0 - 2eBL\phi \tag{9}$$

In fact,

$$V_a = V_b = V_0 \tag{10}$$

A mathematical model for 3 parts of a valve, a motor and a load are required for analysis of the dynamic behavior of a pneumatic motor system.

In the first place, characteristics of flow rate of a valve are as follows.

$$W_a = q_a(x, p_a) \tag{11}$$

$$W_b = q_b(-x, p_b) \tag{12}$$

The mass flow rate passing through the orifice of the valve is as follows.

$$W = C_d C_0 A_0 X P_u / Tu^{\frac{1}{2}} f(p_r) \tag{13}$$

If dynamic characteristics of the motor chamber are assumed to be a adiabatic process,

$$W_a \left(P_{ai} \dot{V}_a + \frac{V_0}{K \dot{P}_a} \right) / (RT_s) \tag{14}$$

$$W_b \left(P_{bi} \dot{V}_b + \frac{V_0}{K \dot{P}_b} \right) / (RT_s) \tag{15}$$

wherein, the instantaneous rate of change of the control volume is obtained from Expression (8) and (9) as follows.

$$\dot{V}_a = 2eBL\dot{\phi} \tag{16}$$

$$\dot{V}_b = -2eBL\dot{\phi} \tag{17}$$

Expression (14) and (15) are

effectuated when it is assumed that there is no internal leakage between two chambers.

Finally, as for load characteristics of the rotary actuator, the friction torque is obtained from Newton's second law as follows.

$$M - M_c \sin(\dot{\phi}) = j\ddot{\phi} \tag{18}$$

wherein, the driving torque is as expressed in the following expression.

$$M = [(P_a - P_b)eL]B \tag{19}$$

3. Experimental apparatus and method

3.1 Experimental apparatus

As shown in Fig. 3 and 4, the rotary actuator, on which this study was conducted, comprises an auxiliary tank, a FRL unit, a servo valve, a pressure sensor and a flow rate sensor which are installed in the upstream of the rotary actuator, an air dynamometer, a proportional valve, a torque measuring sensor, a speed measuring sensor which are installed in the downstream thereof, and a A/D and D/A converter and a computer for controlling and measuring them full-automatically.

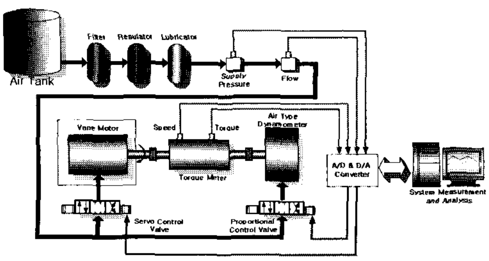

Fig. 3 Schematic of experimental apparatus.

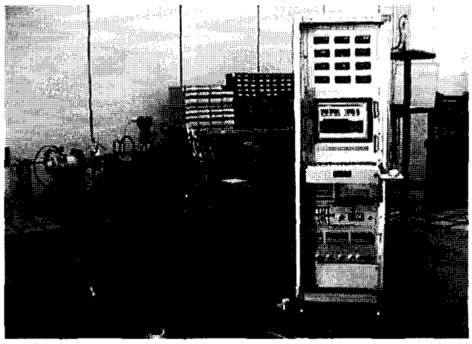

Fig. 4 Photo of experimental apparatus.

3.2 Experimental method

In order to identify characteristics of pressure, flow rate and load of the rotary actuator in the said experimental apparatus as shown in Fig. 3 and 4, experimental data was obtained by the following experimental method.

(1) Operate the servo valve which is the supply flow rate valve.

(2) Regulate the supply pressure by increasing the pressure to 2~6 bar step by step by using the regulator.

(3) Initialize the servo valve and the proportional valve by the D/A converter of the computer.

(4) Set a load capacity by using the dynamometer.

(5) Regulate rpm by increasing the supply flow rate slowly by using the D/A converter of the computer.

(6) Set the intended rpm by the point-to-point method, and use the PID control algorithm. Wherein, the allowable error is ±2rpm.

(7) When rpm reaches the intended value, obtain such data as supply pressure, flow rate, rpm, torque, etc. through the A/D converter, save and indicate them.

(8) When rpm reaches the maximum value, stop operating the servo valve and the proportional valve.

(9) As a result of conducting an experiment on the monitor, if the button of "Graph" is clicked, such data as obtained by respective rpm's through each sensor can be identified by digital values corresponding thereto.

4. Experimental results and discussion

So far, theoretical characteristics of the rotary actuator, the experimental apparatus and the experimental method have been examined. In this section, an explanation is given about respective relations between torque and rpm, power and rpm and flow rate and rpm, which are characteristics of the rotary actuator.

Fig. 5 shows the experimental result on a relation between torque and rpm, and it could be known from it that torque and rpm had an inverse proportional relation.

At 0 (zero) rpm, torque values versus supply pressure values were respectively 0.5, 0.75, 0.9, 1.2 and 1.5 kgf · m versus 2, 3, 4, 5, 6 bar, and at 450 rpm, the starting torque got to be maximum. Thereafter, until rpm reached 2,400, rpm and torque had an inverse proportional relation, and there was a tendency that as rpm increased, the torque value decreased. It could be known that the greater the supply pressure was, the greater the corresponding torque value was also.

Fig. 6 shows the experimental result on a relation between power and rpm, and it could be known from it that as rpm increased, the power value also increased, and that when the supply pressure was 6 bar at 2,400 rpm, the power value got to be 3.5 kW. And it could be known that at 300 rpm or below, the power value was unstable.

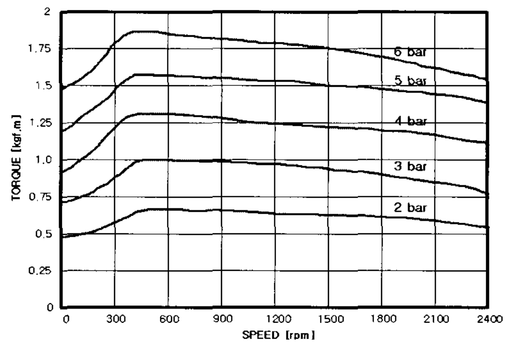

Fig. 5 Torque test results of rotary actuators.

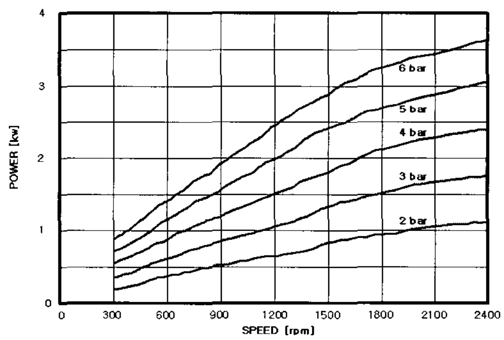

Fig. 6 Power test results of rotary actuators.

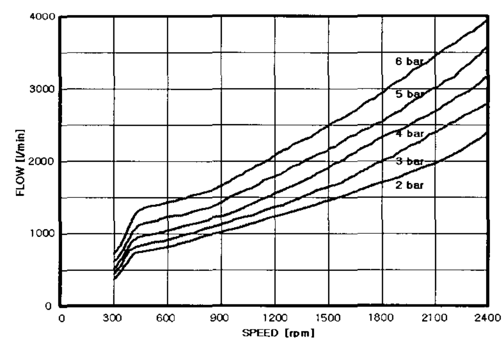

Fig. 7 Flow rate test results of rotary actuator.

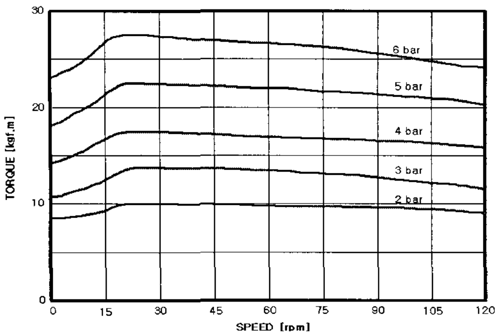

Fig. 8 Torque test results of rotary actuator with worm gear reducer.

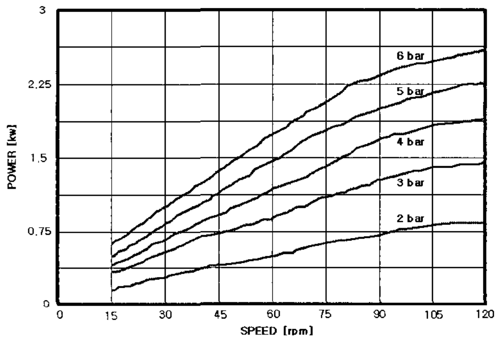

Fig. 9 Power test results of rotary actuator with worm gear reducer.

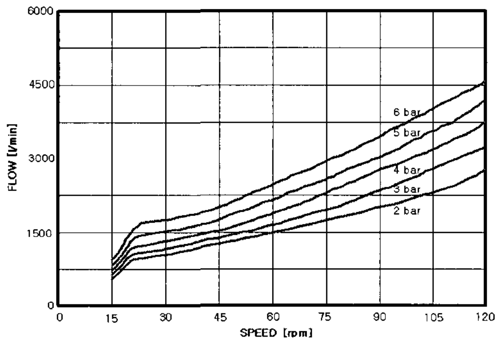

Fig. 10 Flow rate test results of rotary actuator with worm gear reducer.

Fig. 7 is a relation graph of flow rate and rpm, and it could be known from it that flow rate increased in proportion to rpm, and that when the supply pressure was 6 bar at 2,400 rpm, the flow rate got to be approximately 4,000ℓ/min.

And, Fig. 8, 9 and 10 show the results of conducting an experiment on the rotary actuator in which a worm gear reducer having a reduction ratio of 20:1 was installed. They showed characteristics similar to those as shown in Fig. 5, 6 and 7. The power value and the torque value versus rpm, which were characteristics of the rotary actuator, were also found to be respective values corresponding to the reduction ratio of 20:1.

5. Conclusion

As a result of conducting this study on characteristics of the rotary actuator, the following conclusion was obtained.

(1) As a result of conducting an experiment on the pneumatic rotary actuator which was designed and manufactured so that it might have the specification of 4 HP, 2,500rpm and 7.5 nm, torque and rpm had an inverse proportional relation, and it could be known that at 450 rpm, the starting torque, which was the maximum torque vale, was generated.

(2) As for a relation between power and rpm which were characteristics of the pneumatic rotary actuator, as rpm increased, the power value increased parabolically. At the maximum supply pressure and the maximum rpm, the maximum power value appeared, and at 300 rpm or below, a stick slip phenomenon representing an unstable power value took place.

(3) A relation between flow rate and

rpm which were characteristics of the pneumatic rotary actuator was a proportional relation, and at the maximum supply pressure and the maximum rpm, the maximum flow rate value appeared.

(4) The results of conducting an experiment on the 4 HP-class rotary actuator in which a worm gear reducer having a reduction ratio of 20:1 was installed had a tendency that respective torque value, power value and flow rate value versus rpm were similar to those in the case of conducting an experiment on the rotary actuator without such worm gear reducer. The said values were found to be corresponding to the reduction ratio.

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