DEVELOPMENT OF WATER HYDRAULIC CYLINDER POSITION CONTROL SYSTEM

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ABSTRACT

In this paper, the water hydraulic cylinder position control system, newly developed by authors, will be discussed. First, the outline of the water hydraulic servovalve and the components for cylinder position control system, as well as the points of control method of the water hydraulic system, are introduced. Next section discusses on the basic performance of the system: a horizontal cylinder position control; synchronizing control for two horizontal cylinders; and a basic performance of synchronizing control device which moves cylinders vertically. The control performance of these water hydraulic servo system is at the same level of that of the oil hydraulic servo system. For the synchronizing control for vertical cylinders, more practical issue, such as the influence of the eccentric load, is discussed.

KEY WORDS

Water hydraulics, Position control system, Synchronizing control, Water hydraulic servovalve

INTRODUCTION

Potential danger of fire and environmental pollution by oil leakage has been a major concern for conventional use of oil hydraulic system. A growing interest in environmental protection in the recent years has started demanding of setting a higher safety level for hydraulic systems. Further, the regulations toward environmental safety are becoming more tighter than before.

To respond to this trend, fire resistant fluid, such as high water content fluid (HWCF), has developed for fire hazard prevention and it has been used in such as in many fields, the steel industry for example. The main constituent of the fluid is water; however, it requires a special treatment when to be disposed. In short, the fire resistant fluid

cannot be disposed directly into the rivers and the ocean. Considering the disadvantage, the fire resistant fluid is not truly acceptable as environmentally friendly working fluid.

At this point, water hydraulic system, which uses water as the pressure medium instead of oil, is gaining more attention. Water is indeed the most safe fluid for all living things. Because of its specific properties, however, it causes some engineering problems when applying: severe wear induced by low lubricity, rust and erosion, leakage increase by low viscosity and cavitation occurrence for high vapor pressure. Currently, various water hydraulic equipments are under development to overcome such problems through material and design improvements [1,2,3]. These developments enable to create water

hydraulic servo systems that produce clean and high power density.

This paper discusses water hydraulic cylinder position control systems developed by authors that uses tap water as the pressure medium. First, a general description of the developed water hydraulic servovalve is introduced and its comparable performance to conventional oil hydraulic servovalves is explained. The next chapter presents the water hydraulic servo systems, system components, control methods and test results conducted with supply pressure of 70 bar. The test results confirm that the performance of the water hydraulic servo system is about the same as that of conventional oil hydraulic systems, and these prove the applicability of the developed water hydraulic servo system.

WATER HYDRAULIC SERVOVALVE

Figure 1 shows the structure of a developed water hydraulic servovalve [4,5]. This servovalve consists of a torque motor, a flapper-nozzle component, a four-way spool valve, a displacement sensor (LVDT) and a servo amplifier. This is a type of two-stage servovalve that transfers and amplifies the torque motor movement to water hydraulic pressure at the flapper-nozzle component to drive the spool valve. LVDT detects the spool displacement and feeds back to the servo amplifier electrically.

Water, because of its low lubricity, causes direct contact of sleeve and spool and leads to sticking. To prevent sticking of spool to the sleeve in this servovalve, the spool is supported with a set of hydrostatic bearings fitted on the both sides of the sleeve. Furthermore, the water supplied to the hydrostatic bearings is partially utilized in the flapper-nozzle component to reduce power loss by the bearings [6]. In order to reduce the performance degradation risks caused by rust and cavitation erosion, major parts of this servovalve are made of stainless steel. The spool and sleeve are made of industrial ceramics. The

Figure 1 Structure of water hydraulic servovalve

rated pressure of the servovalve is 70 bar and the rated flow rate is 80L/min. Figure 2 shows the appearance of this servovalve.

Figure 3 shows the relationship between the input signal and the flowrate without load pressure. The curve in Figure 3 shows a quite small hysteresis: this indicates that the spool floats in the sleeve by the support of hydrostatic bearings while the spool is positioned by the electrical feedback of displacement.

Figure 4 shows the frequency response characteristics of the spool displacement to the input signal. The amplitude of sine-wave signals are 25% and 50% of the rated input signal (1V) respectively. When the sine-wave signal amplitude is 25% input and the gain is at 3dB decrease, Figure 4 indicates that the break frequency is about 60 Hz. This further indicates that this water hydraulic servovalve has a dynamic characteristic comparable to conventional

Figure 2 Photograph of water hydraulic servovalve

Figure 3 No load flowrate versus input signal

Figure 4 Frequency response of water hydraulic servovalve

oil hydraulic servovalves. To note, the water hydraulic servovalve has passed the endurance test (100% input signal, 10^7 cycles, about 700 hours) per ISO6404-1985.

WATER HYDRAULIC CYLINDER POSITION CONTROL SYSTEM

Equipment and Structure

To conduct the control tests, a water hydraulic servo system is constructed. The system consists of a water hydraulic power unit, two water hydraulic servovalves, two water hydraulic cylinders and a controller. Figure 5 shows the structure of the system that controls the position of the cylinders. Each cylinder is independently controlled by a servovalve assigned to the cylinder. In this way, this system can be used for one-cylinder position control and two-cylinder synchronizing control. The major parts of the cylinders are made of stainless steel. Since tap water is used in the system, sealing systems and seal materials of the cylinders are carefully chosen.

The water hydraulic pump is a radial piston type and the filtered tap water is used as the pressure medium. The supply pressure in the test is 70bar. Pressurized water from the water hydraulic power unit is led to the cylinders via the servovalves. The displacement and velocity of cylinders are controlled by the servovalves. Two loads of

Figure 5 Water hydraulic cylinder position control system

Figure 6 Photograph of water hydraulic cylinder position control system

different weight are directly connected to each cylinder. These loads are supported by linear guides to reduce the friction force. Figure 6 shows the appearance of two-cylinder synchronizing control system.

Outline of Control System

The water hydraulic cylinder position control system is composed as a software servo system. A personal computer is used to control the whole system, which gives a flexibility of installing any control algorithm. In this study, P, PI and PID control are applied selectively. The cylinder stroke is detected by a displacement sensor mounted on the cylinder head and the detected value is fed back to the computer through A/D converter. The computer outputs the calculated values, according to the specified control law, to the servo amplifier through D/A converter and controls the servovalves.

Figure 7 shows the result of one-cylinder position control. The specifications of the cylinder used in the test are as follows: tube diameter is 42 mm; rod diameter is 25 mm; and stroke is 350mm. This test result is the response to the sine-wave input under PI control. The result indicates a desirable control performance, having almost no

Figure 7 Response of one-cylinder position control

waveform distortion.

Figure 8 shows a block diagram of the algorithm of two-cylinder synchronizing control. This consists of two major feedback loops to control cylinders independently and a synchronizing loop to eliminate the displacement difference of the cylinders. The synchronizing loop has a PID controller that minimizes the difference between the average displacement of the two cylinders and displacement of each cylinder. The mean value of the cylinder displacements is used as the correction signal of the minor control loop. Therefore, each cylinder is accelerated when its position is below the mean value: it is decelerated when its position is above the mean value. As a result, the two cylinders are adjusted at the same level. This control algorithm can be easily applied to multi-cylinder systems.

Figure 9 shows an example of the response waveforms to triangular-wave input under two-cylinder control [7]. The specifications of the cylinders used in this test are as follows: tube diameter is 63 mm; rod diameter is 45 mm; and stroke is 500mm. Parameter of each PID controller can be set independently. However, in this test, both PID parameters of each major feedback loop are set the same value to simplify tuning work. Also, both PID parameters of synchronizing loop are set the same value. When the PI control is performed on the two cylinders independently as shown in Figure 9 (a) without synchronizing control, a large position difference between these two cylinders (synchronizing error) occurs at the sudden change of the reference signal. This is due to the subtle differences of cylinder dimensions, servovalve characteristics and load that affects on the cylinders (inertia load in this case) . Figure 9 (b) shows the experimental result of synchronizing control. Here, the error is reduced to about 30% of that observed in Figure 9 (a). This proves the effectiveness of this synchronizing control system.

Figure 8 Block diagram of synchronizing control

APPLICATION TO ELEVATION SYSTEM

Outline of the System

An elevation device driven by multiple cylinders is selected as an application example of water hydraulic cylinder position control system. Physical models of elevation device that contains two vertical cylinders are constructed. The basic performance of the synchronizing control is examined on the models. Two types of elevation device are prepared : one with double-acting single rod cylinders and the other with two-stage double-acting telescopic cylinders. The system structure is the same as the horizontal system explained above. Figure 10 shows the test apparatus with double-acting single rod cylinders.

Position Control Performance

First of all, the synchronizing control performance of the elevation device with double-acting single rod cylinders is examined. Figure 11 shows an example of a position control result to the trapezoid-wave input under no load condition. This is the test result when the reference signal is changed from the cylinder position 50 mm to 450 mm at the velocity 40 mm/s. The specifications of the cylinder is

(a) Without synchronizing control

(b) With synchronizing control

Figure 9 Responses of two cylinders with and without synchronizing control

the same as the one in the horizontal two-cylinder system. For this system, the following selective PI control is applied to the controller of each major feedback loop. Namely, the PI control law is applied when the position error, i.e., the difference between the cylinder displacement and the reference, is less than a threshold value primarily given; the P control is applied when the position error is larger than the threshold value. With this algorithm, fast response without overshoot can be obtained. According to Figure 11, it is clear that the response does not contain overshoot and the maximum synchronizing error is about 2.2 mm in the transient state when the reference signal suddenly changes. In the steady state, the synchronizing error is kept almost zero and the desirable synchronizing control is performed. Secondly, using the same system used above, the influence of eccentric load on the synchronizing control performance

Figure 10 Photograph of elevation device

Figure 11 An example of position control result of an elevation system

of the system is examined. Figure 12 shows the test results examined by the conditions: one is with the load and the other is without the load. As an eccentric load, a weight (500kg) is placed on only one end of the cylinder rod. Compared to the case without the eccentric load on the cylinder in Figure 12 (a), the case with the eccentric load in Figure 12 (b) indicates that the synchronizing error becomes slightly larger during the accelerating and decelerating of cylinder speed. However, this increase of synchronizing error gradually reduces and eventually reaches to zero. This test proves that this water hydraulic elevation system performs well even when an eccentric load is applied on the system.

Figure 13 shows the repeatability of the positioning. This test is to examine the distribution (sample size; $N = 120$) of difference between cylinder reference position and actual cylinder position (position error). The error value is directly read from the dial gauge. The value of cylinder position error is within the range of ± 0.1 mm. The standard deviation of the position error is 0.034 mm. This result promises the system to be used in a wide range of application field.

Finally, the test result of the system with two-stage double-acting telescopic cylinders is introduced. Compared to a standard cylinder, the length of telescopic cylinder can be short, for it can be extended for full stroke. This type of cylinder is beneficial for a system or a machine which size

(a) Without eccentric load

(b) With eccentric load

Figure 12 Influence of eccentric load on the elevation system with synchronizing control

Figure 13 Repeatability of cylinder positioning

is restricted. However, because of the change of effective area at switching point of stages, it is difficult to control its movement at a constant speed and synchronization. Figure 14 shows an example of response results. The telescopic cylinder used is a two-stage double-acting type and its maximum stroke is 1000mm (1st stage: 500mm/ 2nd stage: 500mm). The speed of cylinder movement is 16 mm/s. Even at the switching point of stages, the speed of cylinder movement is controlled almost constant and desirably synchronizing-controlled. For a faster movement of the cylinder, however, synchronizing control performance would be degraded and the reference speed could not be achieved at the switching point of stages.

CONCLUSIONS

This research is aimed to construct safe, clean and environmentally friendly water hydraulic servo systems. This paper intends to introduce the development of water hydraulic cylinder position control system controlled by water hydraulic servovalves. Various tests introduced here confirmed that the water hydraulic cylinder position control system that uses tap water as the pressure medium has a comparable performance to that of the oil hydraulics. In a present situation, obstacles, such as technical difficulties, reliability and costs, still remain when to construct the water hydraulic systems. On the other hand, people in many countries are aware of the importance of fire safety and environment protection and are more interested in the water hydraulics. Having such a strong backup, we will continue to develop the water hydraulic systems while applying excellent features of water hydraulics to the various conventional systems. It is our hope that the water hydraulic systems quickly spread and are widely used in a variety of industries and applications in the very near future.

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Figure 14 Response of synchronizing control system using telescopic cylinders

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