High efficiency of n-level pressure hybrid power supply hydraulic servo system

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Abstract
In a constant pressure valve-controlled hydraulic servo system, the response is excellent but the efficiency is deteriorated. In a load-sensing pump-controlled hydraulic servo system, the efficiency is excellent but the response is desired to be improved. In this study, a N-level pressure hybrid power supply is proposed to realize high efficiency and high response simultaneously. In this paper, the characteristics and the working principle are described. An experimental setup of a 2-level pressure hybrid power supply is used to conduct the experiments. Power consumption of the system is also measured. Experimental results show that the efficiency is improved compared with a conventional constant pressure valve-controlled hydraulic servo system. And another high response type of the N-level pressure hybrid power supply is also proposed.
Key words: HYBRID POWER SUPPLY, HYDRAULIC SERVO SYSTEM, HIGH EFFICIENCY

1. Introduction

Hydraulic servo system is widely used in many fields, such as national defense, aerospace, mining and construction machinery, industrial and marine engineering because of its characteristics, such as large driving force, light weight and small size, fast response, high control accuracy and so on.

There are valve-controlled hydraulic servo system and pump-controlled hydraulic servo system in the hydraulic servo system. In a constant pressure valve-controlled hydraulic servo system, a relief valve is used to keep the supply pressure for the servo valve to be constant. The response of a constant pressure valve-controlled hydraulic servo system is excellent [1, 2]. However, because excess flow rate with high pressure is always dumped to the tank through the relief valve, the efficiency of the system is deteriorated [3, 4]. Also the constant supply pressure generates the excess throttling loss in the servo valve when the load varies. Consequently, the efficiency of the constant pressure valve-controlled hydraulic servo system is worse than a load-sensing pump-controlled hydraulic servo system [5-9]. Regarding a load-sensing pump-controlled hydraulic servo system, several approaches have been widely used, such as the displacement control of a variable displacement piston pump, and the rotational speed control of a fixed displacement pump, etc, to varying load conditions [10,11]. However, how to realize the high response of a load-sensing pump-controlled hydraulic servo system is still in the progress [12, 13].

In order to realize high response, it is necessary that there are the valve-control and a high response power supply in the hydraulic system. In order to realize high efficiency, the load-sensing is important. In the paper, a hydraulic servo system by the use of N-level pressure hybrid power supply is proposed to realize high efficiency and high response simultaneously.

2. N-level Pressure Hybrid Power Supply

As mentioned above, to achieve high response, the valve-controlled and a high response power supply are essential. And to achieve high efficiency, supply pressure and flow must adapt to the load [14, 15]. N-level pressure hybrid power supply has not only the high response characteristic, but also can adapt to the load. So a hydraulic servo system with N-level pressure hybrid power supply has high efficiency and high response. It is more efficient than the constant pressure valve-controlled hydraulic servo system. At the same time its response is faster than the load-sensing pump-controlled hydraulic servo system [16, 17].

As shown in dash box in Fig.1, a pump with unload valve, N accumulators with different applied pressure and N On/Off valves at the inlet of N accumulators are used to consist of a N-level pressure hybrid power supply. Comparing with the constant pressure hydraulic power supply as shown in dash box in Fig.2, it has some differences. First, an unload valve is connected to the side of the fixed-displacement pump [18]. Second, N accumulators are used instead of the relief valve [19]. According to the load, the applied pressures of the accumulators are set to be in N pressure levels (i.e. p_1, p_2,…, p_n) from low to high.

During the time system running, when an accumulator whose pressure adapt to the load is chosen, the On/Off valve at the inlet of the selected accumulator is opened, and the selected accumulator is connected to the servo valve. Then supply pressure to the servo valve will reach to the pressure of the selected accumulator in a moment. Consequently supply pressure adapt to the load very fast.

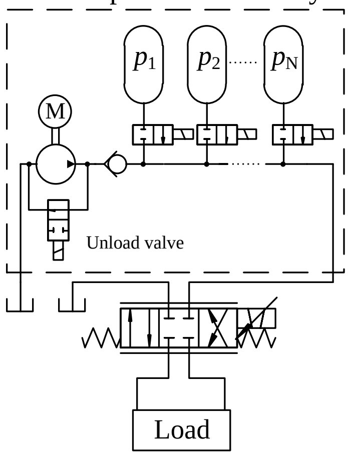


Figure 1. N-level pressure valve-controlled hydraulic servo system

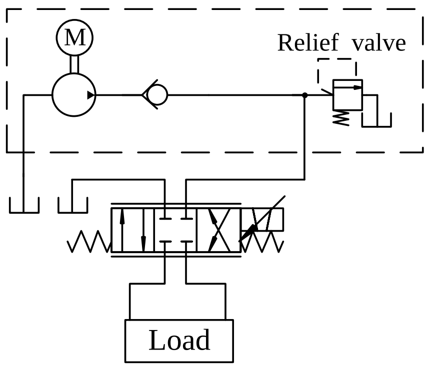


Figure 2. Constant pressure valve-controlled hydraulic servo system

Moreover, at the beginning period of the selected accumulator connected to the servo valve, the pump supplies the oil to both the servo valve and the accumulator. And the pump is unloaded after the pressure of the selected accumulator reaches to the maximum value. After the pump is unloaded, the selected accumulator supplies oil to the servo valve.

The hydraulic servo system with N-level pressure hybrid power supply has no excess oil flow back into the tank from the relief valve. And because N-level supply pressure to the servo valve by N accumulators can adapt to the load, there is no excess throttling loss in the servo valve. So the efficiency of the hydraulic servo system with N-level pressure hybrid power supply is very high.

And also, in the hydraulic servo system with N-level pressure hybrid power supply, supply pressure will reach to the appropriate pressure to the load in a moment by switching the accumulator, the response of the system is very high[20, 21].

3. Another Type of N-level Pressure Hybrid Power Supply

There are N ON/OFF valves at the inlet of the accumulators in the N-level valve-controlled hydraulic servo system as shown in Fig.1. The construction of this type of the N-level pressure hybrid power supply is simple. But in this type, supplying flow from an accumulator to the system and filling flow from pump to an accumulator are controlled by the same ON/OFF valve. So that, an accumulator can be filled only the period the pump supplies the oil to the servo valve. Therefore, on the occasion when input signal frequency is very fast, accumulators cannot be filled sufficiently.

So another type of N-level pressure hybrid power supply is proposed in this paper. As shown in Fig.3, new type has two ON/OFF valves at the inlet of each accumulator.

Pressurized oil is supplied from the accumulators to servo valve through ON/OFF valves (V_{AV1},V_{AV2},…, V_{AVN}). Also, accumulators are filled by pressurized oil from pump through ON/OFF valves (V_{PA1},V_{PA2},…,V_{PAN}). The supply circuit from an accumulator to servo valve is separated from the filling circuit of an accumulator. Consequently, the accumulator can be filled, regardless of whether the accumulator supplies oil to the servo valve or not. It means that the accumulators in new type N-level pressure hybrid power supply can be filled sufficiently in high-frequency switching condition.

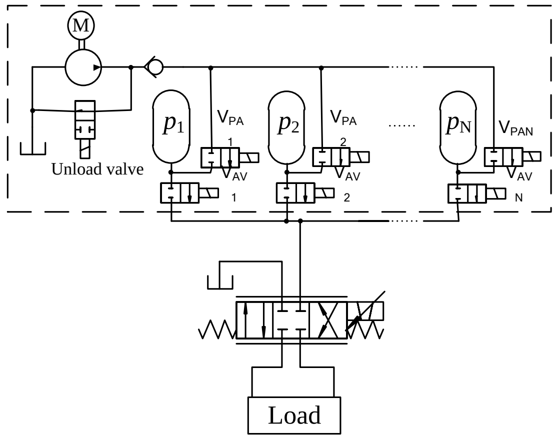


Figure 3. N-level pressure valve-controlled hydraulic servo system (another type)

Because the purpose of experiments in this paper is to verify high efficiency of the N-level pressure hybrid power supply, switching frequency of accumulators is not so high. Therefore, the N-level pressure hybrid power supply as shown in Fig.1 is used in this paper.

4. 2-Level Pressure Hybrid Power Supply

To illustrate action principle of the N-level pressure valve-controlled hydraulic servo system, a 2-level pressure valve-controlled hydraulic servo system as shown in Fig.4 is constructed. As shown in Fig.4, there are a high pressure accumulator and a low pressure accumulator. Pressure of the high pressure accumulator is p_H. Its range is 8.4MPa to 8.7MPa. Pressure of the low pressure accumulator is p_L. Its range is 2.6MPa to 2.77MPa. The parameters of the devices are shown in *Table 1*. To switch quickly, two servo valves at the inlet of accumulators are used as the ON/OFF valves. Input signals of two servo valves are -10V to 10V. They are produced by Yuken Kogyo Co., Ltd. (Type:F-LSVG-10-60-10. Frequency:330Hz@-3dB/410Hz@-90°).

To illustrate the system action principle and verify high efficiency of the system, the input signal as shown in Fig.5 is used. There are the target displacement and the target force in the period of 20s. As shown in Fig.5, when the cylinder reaches 50mm after 9s, it begins to compress the spring. It begins to press on the fixed wall as reaching 67mm at 13.5s. It runs back after 16.5s. So force control is used from 13.5s to 16.5s in pressing on the fixed wall (Force target: 5700N), and position control is used in other period.

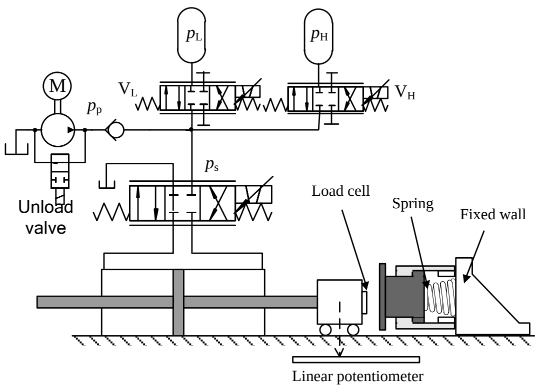


Figure 4. Schematic of experimental setup

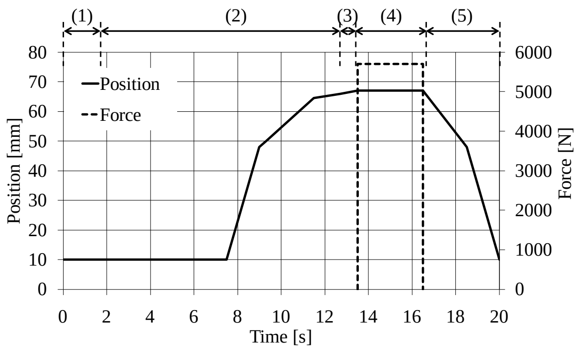


Figure 5. Target position and force

Table 1. Specification of the experimental setup

Press force	5700N, max
Cylinder	Piston diameter: 22mm Head diameter: 40mm Stroke: 150mm
Spring	26.1 N/mm
Low pressure accumulator	Volume: 4L
High pressure accumulator	Volume: 4L
Pump	6L/min, 1500rpm

According to unload valve and two valves at the inlet of two accumulators, there are four states in the 2-level pressure valve-controlled hydraulic servo system as shown in *Table 2*. In the state "LL" and "LU", the low accumulator is connected to the system, and p_s (supply pressure to the servo valve for controlling load) is equal to p_L(pressure of the low accumulator). In the state "LL", pump is loaded. It means pump supplies oil to the low accumulator and the servo valve. In the state "LU", pump is unloaded. It means the low accumulator supplies oil to the servo valve. In the state "HL" and "HU", the high accumulator is connected to the system, and p_s is equal to p_H (pressure of the high accumulator). In the state "HL", pump is loaded. It means pump supplies oil to the high accumulator and the servo valve. In the state "HU", pump is unloaded. It means the high accumulator supplies oil to servo valve. So, it can supply two pressures to the servo valve for adapting load by switching V_L and V_H (two valves at the inlet of two accumulators).

To keep the efficiency to be high, the phases of force control are in the high pressure mode and the phases of position control are in the low pressure mode.

Table 2. Four states of power supply

State	Control valve of accumulator	Pump
LL	V_L: 10V; V_H:-10V	Load
LU	V_L: 10V; V_H:-10V	Unload
HL	V_L: -10V; V_H:10V	Load
HU	V_L: -10V; V_H:10V	Unload

Table 3. Switching conditions of valves

	Switching conditions	Change of valve state
Phase(1)→Phase(2) (LL→LU)	p_L > 2.77MPa	Unload valve: unload
Phase(2)→Phase(3) (LU→HL)	Displacement increases to 66mm	1.Unload valve: load 2.V_L: -10V; V_H: 10V
Phase(3)→Phase(4) (HL→HU)	p_H > 8.7MPa	Unload valve: unload
Phase(4)→Phase(5) (HL→LU)	Displacement decreases to 66.9mm	V_H: -10V; V_L: 10V

There are five phases in the position signal as shown in Fig.5. The states are shown in *Table 2*. In the initial state, p_L is 2.6MPa and p_H is 8.4MPa. At first, there is the state "LL" in the phase(1). Because the pump is supplying oil to the low accumulator and system, p_s and p_L are rising. After p_L >2.77MPa, it reaches the phase(2) on the state "LU". The low accumulator is supplying oil to the servo valve and the pump is unloaded. Before the force control, it reaches the phase(3) on the state "HL" when the piston reaches 66mm. The pump is loaded and p_s and p_H are rising. After p_H >8.7MPa, it reaches the phase(4) on the state "HU". The high accumulator is supplying oil to the servo valve and the pump is unloaded. When the cylinder returns to 66.9mm after force control, it reach the phase(5) which is the same case as the phase(2). The switch conditions and valve changes between phases are shown in *Table 3.*

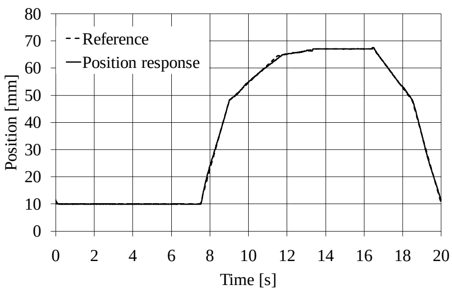
As mentioned above, hydraulic power supply can be quickly converted between two accumulators and pump by controlling unload valve and two high-speed valves (V_L and V_H). So it can be achieved that high response and high efficiency of the hydraulic servo system by the use of 2-level pressures hybrid power supply.

5. Experiments

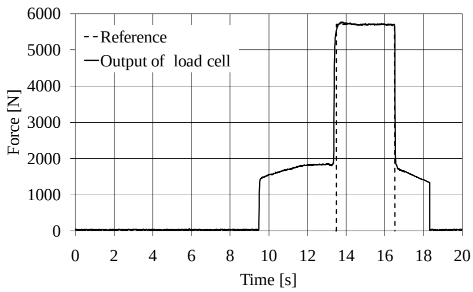
5.1 Experiment I

To verify the efficiency of the 2-level pressure valve–controlled hydraulic servo system, experiment is performed. Hydraulic circuit and experimental devices are the same as that shown in Fig.4. Position signal is the same as that shown in Fig.5. The servo valve to control the load is produced by Yuken Kogyo Co., Ltd. (Type: LSVG-10-10-10, frequency: 350Hz@-3dB 450Hz@-90°). The unload valve is produced by Hirose Valve Industry Co., Ltd (Type: HSO-T03-A10F-21). When the servo system is running, p_L is kept between 2.6MPa and 2.77MPa and p_H is kept between 8.4MPa and 8.7MPa.

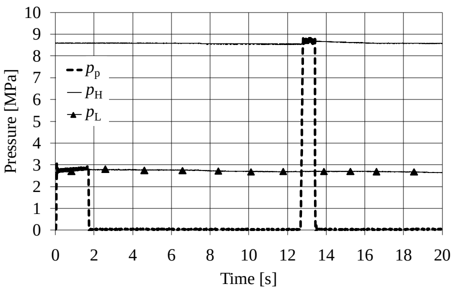
Experimental results are shown in Fig.6. The position response is shown in Fig.6(a). The output force is shown in Fig.6(b). It is verified that position response and force response are very good by the 2-level pressure valve-controlled hydraulic servo system. The supply pressure for the servo valve to control the load, shown in Fig.6(d) adapt to the load. The pump pressure (p_p) and the pressures of two accumulators (p_H, p_L) are shown in Fig.6(c). The pump is loaded just when accumulators are filled. Loaded time of the pump in the 2-level pressure valve-controlled hydraulic servo system is very short. It can be concluded that fluid power generated by the pump in the 2-level pressure valve-controlled hydraulic servo system is 93% less than that in a constant pressure valve-controlled hydraulic servo system.



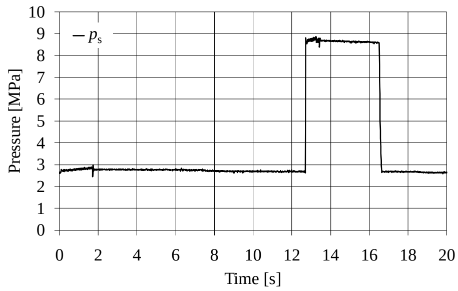
(a) Position



(b) Force



(c) Pressure of pump and two accumulators



(d) Supplied pressure to the servo valve

Figure 6. Results of experiment I

5.2 Experiment II

Hydraulic circuit and experimental devices of experiment II are the same as that of experiment I. The pump flow is 15L/min. As shown in Fig.7, the sinusoidal signal is used as the position signal. The period is 2s and amplitude is 25mm. When the cylinder reaches 10mm, it begins to compress the spring. The spring force becomes maximum in 25mm which is the maximum position of the cylinder. The spring force is shown in the dotted line in Fig.7.

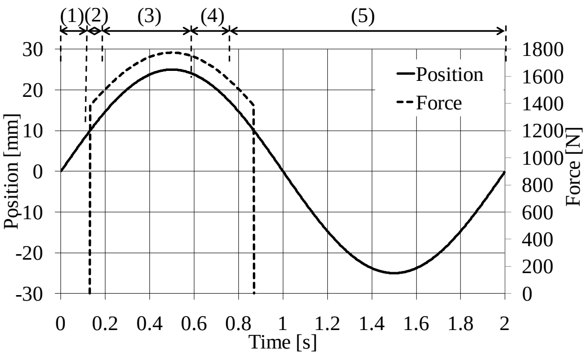
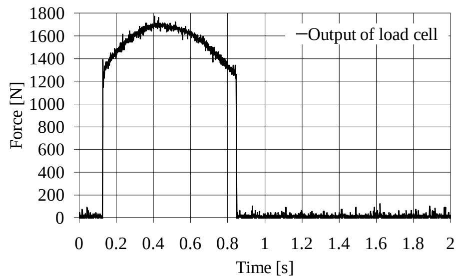
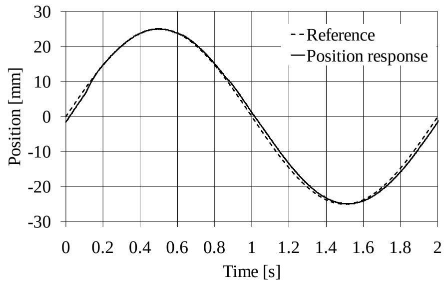


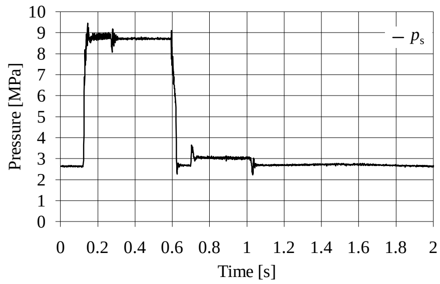
Figure 7. Target position and force in experiment II



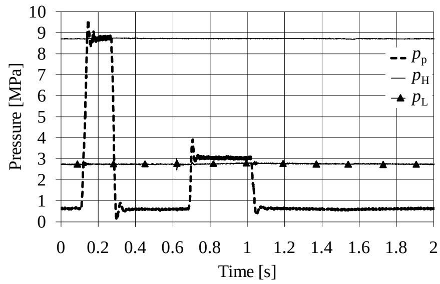
(a) Position



(b) Force



(c) Pressure of pump and two accumulators



(d) Supplied pressure to the servo valve

Figure 8. Results of experiment II

In the initial state, p_L is 2.7MPa and p_H is 8.4MPa. States of the 2-level pressures hybrid power supply and valve changes between phases are the same as that shown in *Table 2* and *Table 3*.

There are five phases in the position signal as shown in Fig.7. At first, there is the state "LU" in the phase(1). It reaches the phase(2) on the state "HL" when the piston reaches 9mm. After p_H >8.7MPa, it reaches the phase(3) on the state "HU". When the cylinder returns to 24mm, it reaches the phase(4) on the state "LL". After p_L>2.77MPa, it reaches the phase(5) which is the same case as phase(1). The states and switching condition between states are like experiment I.

Experimental results are shown in Fig.8. As shown in Fig.8(a) and Fig.8(b), it is verified that position response and force response is very good by the 2-level pressure valve-controlled hydraulic servo system. From p_s as shown in Fig.8(d), it is verified that supply pressure to the servo valve adapt to the load. From p_p, p_H and p_L as shown in Fig.8(c), it is verified that the pump is unloaded just when accumulators are filled.

It can be concluded that fluid power generated by the pump in the 2-level pressure valve-controlled hydraulic servo system is 80% less than that in a constant pressure valve-controlled hydraulic servo system[22].

5.3 Power Consumption

From experimental results in 5.1 and 5.2, it is concluded that the 2-level pressure valve-controlled hydraulic servo system can save fluid power. But the major consumer of the system is electric power. When pump is unloaded, the consumption of fluid power is 0. But the consumption of electric power isn't 0 since motor is always running. The electric power of the 2-level pressure valve-controlled hydraulic servo system in the experiments is shown in *Table.4*.

Table 4. Consumption of electric power in experiments

	The constant pressure valve-controlled hydraulic servo system (Wh)	The 2-level pressure valve-controlled hydraulic servo system			
		Motor is always running		Motor is stopped when pump is unloaded	
		Electric power (Wh)	The reduction rate of electric power (%)	Electric power (Wh)	The reduction rate of electric power %
Experiment I	561	273.8	51.2	84.4	85.0
Experiment II	879	387	56.0	246	72.0

As shown in *Table 4,* in experiment I, the electricity consumption of the 2-level valve-controlled pressure hydraulic servo system is 51.2% less than the constant pressure valve-controlled hydraulic servo system when motor is always running, and it is 85% less than the constant pressure valve-controlled hydraulic servo system when motor is stopped in the state "LU" and "HU" .

As shown in *Table 4*, in experiment II, the electricity consumption of the 2-level valve-controlled pressure hydraulic servo system is 56% less than the constant pressure valve-controlled hydraulic servo system when motor is always running, and it is 72% less than the constant pressure valve-controlled hydraulic servo system when motor is stopped in the state "LU" and "HU" .

So, it is concluded that the efficiency of the servo system proposed in this paper is greatly improved compared with a constant pressure valve-controlled hydraulic servo system from fluid power and electric power. The fluid efficiency of the 2-level valve-controlled pressure hydraulic servo system is higher than the electricity efficiency when motor is stopped in the state "LU" and "HU", and the electricity efficiency is higher than that as motor is always running.

6. Conclusions

In this paper, two types of N-level pressure hybrid power supply are proposed. The hydraulic servo system by the use of the N-level pressure hybrid power supply is constructed and its characteristics are described. An experimental setup of a 2-level pressure hybrid power supply is used to conduct the experiments. Though comparative experiment between the 2-level pressure valve-controlled hydraulic servo system and the constant pressure valve-controlled hydraulic servo system, high efficiency of 2-level pressure hybrid power supply is confirmed. From the point of the actual power consumption, the efficiency of the system is the highest when motor is stopped in the state of unload.

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