A NEW COMPENSATION METHOD FOR IMPROVING STATIC CHARACTERISTICS OF A PROPORTIONAL POPPET VALVE

Wu Pingdong*, Hitoshi Maekawa, Kazushi Sanada**
Ato Kitagawa**, Toshio Takenaka***

*Dept. of Control Engineering
Beijing Institute of Technology
Beijing, China

**Dept. of Control Engineering, Faculty of Engineering
Tokyo Institute of Technology
Tokyo, Japan

***Dept. of Mechanical Engineering, Faculty of Engineering
Musashi Institute of Technology
Tokyo, Japan

ABSTRACT

A proportional poppet valve is a new oil-hydraulic valve whose main poppet lift is linearly controlled by a pilot valve. Like a usual and simple oil-hydraulic valve, the total flow rate of this new poppet valve is influenced by load pressure. The present paper describes a new compensation method to decrease the influence of load pressure, and this new method is named as area compensation method. The area compensation method is based on the design of top and bottom areas of the main poppet. From detailed experiments and analysis, this new compensation method has been found to be effective and practical. The structure of the proportional poppet valve designed by this area compensation method is simple. The analysis of static characteristics is easily and accurately performed.

KEYWORDS

Oil-hydraulic Control Valve,
Proportional Poppet Valve,
Static Characteristics,
Compensation Method

NOMENCLATURE

A_c : top area of main poppet
 A_r : bottom area of main poppet on which load pressure acts
 A_s : bottom area of main poppet on which supply pressure acts
 c_c : discharge coefficient of control orifice
 c_m : discharge coefficient of main valve

c_v : discharge coefficient of pilot valve
 D : poppet diameter
 f_v : opening area of pilot valve
 p_c : control pressure
 p_r : load pressure
 p_s : supply pressure
 q_c : flow rate through control orifices
 q_m : flow rate through main poppet valve
 q_r : flow rate through load valve
 q_v : flow rate through pilot valve
 S_r, S_s : area ratios
 W_c : width of control orifices
 W_m : coefficient of opening area of main poppet valve
 x : lift of main poppet
 x_t : underlap of control orifices
 ρ : oil density

Fig.1 Schematic diagram of a proportional poppet valve

INTRODUCTION

A proportional poppet valve is a new oil-hydraulic valve whose main poppet lift can be linearly controlled by a pilot valve. A schematic diagram of the proportional poppet valve is presented in Fig.1. This valve is mainly constructed with a poppet valve ①, control orifices ② and a pilot valve ③. Control orifices are the grooves on the side surface of the main poppet. During steady state condition, the main poppet lift can be linearly controlled by the pilot valve, since oil flow rate through control orifices equals oil flow rate through the pilot valve. This new type of valve was proposed by B.Andersson(1), and was named as proportional poppet valve. The fundamental static and dynamic characteristics of this proportional poppet valve have been investigated by the authors(2)~(4).

Like a usual and simple oil-hydraulic valve, the total flow rate of this new poppet valve is influenced by load pressure. The present paper describes a new compensation method to decrease the influence of load pressure on the total flow rate of the proportional poppet valve. This compensation method was proposed by one of the authors, P.WU, and was named as area compensation method. The area compensation method is based on the design of top and bottom areas of the main poppet to compensate the influence of load pressure. The structure of the valve designed by this area compensation method is very simple. The analysis of static characteristics can be easily and accurately performed.

EXPERIMENTAL CIRCUIT

An experimental oil-hydraulic circuit is presented in Fig.2. Experiments were conducted to test static characteristics of the proportional poppet valve ① which was used as a flow control valve. Oil flow was generated by a piston pump ⑧ and the flow pressure was limited by a relief valve ⑨. The pressure setting of the relief valve was 5 MPa during experiments. Flow rate was controlled by the proportional poppet valve ①. Pressure at the outlet of the poppet valve ① was measured by a pressure gauge ④. Oil flow from the poppet valve ① was made to pass through the throttle valve ⑪ which was used as a load valve. The flow rate through the throttle valve ⑪ was measured by a flow meter ⑩. In this experiment, two kinds of pilot valves were used. One was a simple throttle valve ③

and another was a pressure-compensated flow control valve ②. Selection of these two pilot valves was made possible by a directional control valve ⑤. For measuring oil flow rate through the pilot valve, another directional control valve ⑦ was operated and the pilot oil flow was led to a flow meter ⑥.

FUNDAMENTAL STATIC CHARACTERISTICS

Static Characteristics of an Uncompensated Valve

In this section, fundamental static characteristics of an uncompensated proportional poppet valve are briefly described(2). Referring to Fig.1, following equations are easily obtained.

- Flow rate through main poppet valve

$$q_m = C_m W_m x \sqrt{\frac{2}{\rho} (p_s - p_r)} \quad (1)$$

- Flow rate through pilot valve
(a simple throttle valve)

$$q_y = C_y f_y \sqrt{\frac{2}{\rho} (p_c - p_r)} \quad (2)$$

- Flow rate through control orifices

$$q_c = C_c W_c (x + x_i) \sqrt{\frac{2}{\rho} (p_s - p_c)} \quad (3)$$

Continuity equations on steady state condition are written as

$$q_y = q_c \quad (4)$$

$$q_r = q_m + q_y \quad (5)$$

Fig.2 Experimental circuit

On steady state condition, three forces caused by pressures (supply pressure, load pressure and control pressure) and a steady state flow force act on the main poppet valve. Comparing with other three forces, the steady state flow force is small enough to be omitted. In the case of the proportional poppet valve used in experiments, the steady state flow force was only about 3% of total force. Therefore in this analysis, steady state flow force was omitted. For the forces acting on the main poppet to be in equilibrium, the following relation among supply pressure p_s , load pressure p_r and control pressure p_c is necessary;

$$p_c = S_s p_s + S_r p_r, \quad (6)$$

where

$$S_s = \frac{A_s}{A_c} \quad \text{and} \quad S_r = \frac{A_r}{A_c}. \quad (7)$$

From Eq. (2)~Eq. (4) and Eq. (6), the main poppet lift x is given by

Fig.3 Static characteristics of an uncompensated proportional poppet valve

Table 1 Symbols and pilot valve opening area f_y in Fig.3, Fig.7 and Fig.8

		f_y (mm ²)
①	●	0.12
②	▲	0.24
③	○	0.48
④	△	0.60

$$x = \frac{c_y}{c_c W_c} \sqrt{\frac{S_s p_s + (S_r - 1) p_r}{(1 - S_s) p_s - S_r p_r}} \cdot f_y - x_i. \quad (8)$$

For a usual poppet valve, the following relation exists between area ratios;

$$S_s + S_r = 1 \quad (9)$$

Combining Eq. (8) and Eq. (9),

$$x = \frac{c_y}{c_c W_c} \sqrt{\frac{S_s}{S_r}} \cdot f_y - x_i. \quad (10)$$

From Eq. (1), Eq. (3)~Eq. (6) and Eq. (9), the total flow rate is given by

$$q_r = c_m W_m x \sqrt{\frac{2}{\rho} (p_s - p_r)} + c_c W_c (x + x_i) \sqrt{\frac{2}{\rho} S_r (p_s - p_r)}. \quad (11)$$

From Eq. (10) and Eq. (11), it becomes clear that the lift x and the total oil flow rate q_r can be linearly controlled by the pilot valve opening f_y . It is also obvious that the total flow rate q_r is considerably influenced by load pressure p_r . Experimental results of relations between q_r and p_r for various pilot valve opening areas f_y are presented in Fig.3. Symbols in Fig.3 are explained in Table 1. As load pressure p_r increases, total flow rate q_r decreases. When load pressure p_r equals supply pressure p_s (=5 MPa), the total flow rate q_r becomes zero. From these experimental results, it becomes clear that the total flow rate of an uncompensated proportional poppet valve is considerably influenced by load pressure.

Compensation Method by a Pressure-compensated Flow Control Valve

It is evident from considerations of the above section that an uncompensated proportional poppet valve is not suitable for a flow control valve, since the total flow rate is considerably influenced by load pressure. Usually, in order to improve static characteristics, a pressure-compensated flow control valve is used as a pilot valve(5). In this case, the pilot flow rate q_y is not influenced by load pressure p_r or control pressure p_c . The main poppet lift x is given by

$$x = \frac{1}{c_c W_c} \sqrt{\frac{\rho}{2 S_r (p_s - p_r)}} \cdot q_y - x_i, \quad (12)$$

and the total flow rate q_r is given by

$$q_r = c_m W_m x \sqrt{\frac{2}{\rho} (p_s - p_r) + q_{s.}} \quad (13)$$

As is evident from Eq. (12), the lift x linearly varies with the pilot flow rate $q_{s.}$. When the load pressure p_r increases, the lift x increases. An increment in the poppet lift compensates the decrement in flow rate caused by load pressure. The experimental results of static characteristics of the proportional poppet valve with a pressure-compensated flow control valve are presented in Fig.4. In Fig.4, plots represent experimental results for three flow-rate settings of the pilot valve. Comparing with results of an uncompensated valve presented in Fig.3, static characteristics presented in Fig.4 are more favorable. However, the use of a pressure-compensated flow control valve may cause problems, in that the valve structure becomes complicated and that the analysis of static characteristics is very difficult.

NEW COMPENSATION METHOD

In this chapter, a new compensation method to improve static characteristics of a proportional poppet valve is described. The new method is named as area compensation method. The area compensation method is the design method of area ratios to improve static characteristics of a proportional poppet valve. And in this method, instead of using a pressure-compensated flow control valve, a simple throttle valve is used as a

Fig.4 Static characteristics of a proportional poppet valve with a pressure-compensated flow control pilot valve

pilot valve. In this case, the relation between the main poppet lift x and the pilot valve opening f , is given by Eq. (8). In the above chapter, it was assumed that sum of area ratios S_r and S_s equals unity. In area compensation method, the sum of these area ratios is greater than unity, i.e.,

$$S_s + S_r > 1. \quad (14)$$

Eq. (14) means that the sum of bottom areas A_s and A_r is greater than the top area A_c . As an example, the structure of such a proportional poppet valve is presented in Fig.5. A rod of small diameter is attached at the top of main poppet on which the control pressure p_c acts, thereby making the area A_c smaller than sum of areas A_s and A_r .

Total flow rate of a valve compensated by the area compensation method is obtained from Eq. (1), and Eq. (3) ~ Eq. (6);

$$q_r = c_m W_m x \sqrt{\frac{2}{\rho} (p_s - p_r) + c_c W_c (x + x_i)} \times \sqrt{\frac{2}{\rho} [(1 - S_s) p_s - S_r p_r]}. \quad (15)$$

Poppet lift x is given by Eq. (8). Using Eq. (8) and Eq. (15), static characteristics can be calculated. In Fig.6, calculated results for a proportional

Fig.5 Proportional poppet valve with a rod of small diameter

poppet valve whose area ratios S_r and S_s equal 0.50, 0.55 and 0.60 are presented. A valve whose area ratios equal 0.50 is a usual poppet valve. According to area ratios, the proportional poppet valve has different static characteristics. Many calculations of static characteristics of proportional poppet valves of various area ratios were carried out. From these results, area ratios were determined to be 0.55 for the proportional poppet valve used in experiments. Experimental results and calculated results of static characteristics of a compensated valve ($S_r = S_s = 0.55$) are presented in Fig.7. Symbols used in Fig.7 are explained in Table 1. Comparing with static characteristics of an uncompensated valve presented in Fig.3, static characteristics presented in Fig.7 is much more favorable for a flow control valve. In Fig.8, experimental results of lift x of this compensated valve are

presented. Symbols used in Fig.8 are also explained in Table 1. When the load pressure increases, the main poppet lift also increases. Therefore the decrement in oil flow rate can be compensated by the increment in the poppet lift. In Fig.7 and Fig.8, calculated results showed a good agreement with experimental results. From these results, it has become clear that the area compensation method is effective and that static characteristics of a proportional poppet valve designed by the area compensation method are accurately predicted by calculations.

As an example of prediction of static characteristics, calculated results of static characteristics for two supply pressures and for two poppets of diameter of a proportional poppet valve designed by the area compensation method are presented in Fig.9 and Fig.10. Calculations were performed for several pilot valve opening

Fig.6 Computed results of static characteristics of proportional poppet valves of various area ratios

Fig.7 Experimental results of static characteristics of a proportional poppet valve designed by area compensation method

Fig.8 Experimental results of poppet lift of a proportional poppet valve designed by area compensation method

areas f_v . Calculated results for two supply pressures ($p_s=5$ and 20 MPa) are presented in Fig.9. As supply pressure p_s becomes larger, static characteristics are more compensated. And calculated results for two poppets of diameter ($D=16$ and 20 mm) are presented in Fig.10. As poppet diameter becomes larger, the controllable range of flow rate extends more widely.

CONCLUSION

In this report, the area compensation method of a proportional poppet valve has been investigated. From detailed experiments and considerations, the following has become clear.

- (1) Static characteristics of an uncompensated poppet valve are considerably influenced by load pressure.
- (2) A usual compensation method using a pressure-compensated flow control valve as a pilot valve is effective, but the

valve structure may become considerably complicated.

- (3) The area compensation method is a very effective method.
- (4) The structure of a proportional poppet valve designed by the area compensation method is simple.
- (5) Static characteristics of a proportional poppet valve compensated by the area compensation method can be accurately calculated.

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Fig.9 Static characteristics of proportional poppet valves with supply pressures of 5 and 20 MPa ($S_s = S_r = 0.55$)

Fig.10 Static characteristics of proportional poppet valves of 16 and 20 mm in diameter of a main poppet ($S_s = S_r = 0.55$)