Switching valve operated proportional seat valve with momentum flowmeter

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ABSTRACT

Mobile or stationary fluid power systems require no leak valves with proportional controllability. Following the development of a proportionally controlled seat valve with feedback slots, authors have designed an electrohydraulic seat valve with a momentum flowmeter which compensates the flow fluctuation of the valve against load pressure changes. The flow control seat valve operated by a PWM switching valve controls flow rates of 80 L/min within 0.1s. The paper shows transient characteristics of the valve and its simulation results by bond graph analyses.

KEYWORDS

Fluid Power Systems, Oil Hydraulics, Proportional Seat Valve,
PWM Switching Valve, Momentum Flowmeter, Flow Control System

NOMENCLATURE

A : cross sectional area of flowmeter
 A_c : control chamber area of main valve
 A_p (A_{p_m}): pilot valve opening area ($_m$: max.)
 A_s : supply pressure acting area
 b : damping coefficient of flowmeter spool
 C_d : discharge coefficient
 F_f : flow force
 k_1, k_2 : spring constants
 L : length between inlet and outlet port
 m : mass of flowmeter spool
 m_f : mass of working fluid moving with spool
 P_c : pressure at control chamber

P_L : load pressure
 P_s : supply pressure
 Q : flow rates
 Q_c : flow rates through feedback slots
 Q_L : load flow rates
 Q_p : pilot flow rates
 t_p : PWM width
 t_s : PWM carrier
 W_c : width of feedback slots
 x : lift of main seat valve
 x_L : underlap of feedback slots
 y : displacement of flowmeter spool
 ρ : fluid density
 τ : PWM duty ($= t_p / t_s$)

κ : area ratio ($= A_s / A_c$)
 θ : discharge angle of jet

INTRODUCTION

Fluid power systems of construction machinery or extrusion machinery require no leak electrohydraulic control valves which have capabilities of continuous and wide range flow control and quick response control under high pressure. Following the development of a proportionally controlled seat valve^{(1), (2), (3)} with position feedback slots, authors have designed an electrohydraulic seat valve operated by a PWM switching pilot valve⁽⁴⁾. The seat valve controls flow rates of 80 l/min within 10 ms in no-load condition by open loop control. The present paper describes a flow control system with proportional controllability insensitive to load pressure disturbances. The system is named the flow sensing seat valve which consists of a combination of the seat valve

and a momentum flowmeter⁽⁵⁾. The paper shows the fundamental characteristics of the flow sensing seat valve and the analytical results of dynamics of the system.

PROPORTIONAL SEAT VALVE OPERATED BY SWITCHING VALVE

Figure 1 shows the configuration of the proportional seat valve. The valve consists of a main seat valve with feedback slots and a pilot valve. The lift of the main valve is expressed by the following equation.

$$x = \frac{A_p}{W_c} \sqrt{\frac{\kappa}{1 - \kappa}} - x_L \quad (1)$$

where A_p is valve opening area of the pilot valve, W_c is width of the slot, κ is area ratio, and x_L is underlap of the slot. Authors apply a switching valve to control the pilot opening area A_p . The main valve opens proportionally to the pilot valve

Fig.1 Proportional seat valve controlled by a PWM switching valve

operation which is controlled by PWM signals⁽⁶⁾. At constant pressure difference, the pilot valve flow rate Q_p is proportional to the duty of pulse width ($= t_p / t_s$). The equivalent opening area of the pilot valve is expressed by

$$A_p = \tau A_{p_m} = \frac{t_p}{t_s} A_{p_m} . \quad (2)$$

The maximum pilot flow rates are 4 L/min at pressure difference of 5 MPa on the PWM currying frequency of 80 Hz. The main valve magnifies flow rates fifty times as large as the pilot valve and controls flow rates of 80 L/min within 10ms.

MOMENTUM FLOWMETER AND BASIC CHARACTERISTICS

Principle of flow measurement

The momentum flowmeter is illustrated in Fig.2. The principle of flow measurement is measuring the flow force acting on the spool⁽⁷⁾. The momentum force balances with the spring force. In Fig.2, the fluid flow from A port to the chamber through the 45° slanted ports makes jet flow with momentum.

The flowmeter is able to measure flow rates of both side flows.

Characteristics of the flowmeter

The flow force working on the spool is expressed by

$$F_f = \rho \frac{Q |Q|}{C_d A} \cos \theta + \rho L \dot{Q} - m_f \ddot{y} \quad (3)$$

where the direction of flow from A to B is defined to be positive. The dynamics of the spool is expressed by

$$m \ddot{y} + b \dot{y} + (k_1 + k_2) y = F_f . \quad (4)$$

From Eq.(4), the steady state displacement is balanced

$$y = \rho \frac{Q |Q|}{C_d A (k_1 + k_2)} \cos \theta . \quad (5)$$

The natural angular frequency of the flowmeter is designed $\omega_n (= \sqrt{(k_1 + k_2) / m}) = 440 \text{ rad/s} (\sim 70 \text{ Hz})$. The steady state characteristics is shown in Fig.3. The steady state characteristics agrees with the

Fig.2 Momentum flowmeter

theoretical relations. The spool works within 2 % hysteresis, however, the resolution in the low flow rates range (below 10 L/min) is not good because of square curve characteristics. Figure 4 shows the transient characteristics of the flowmeter which are compared with pressure changes of the small fluid resistance orifice serially connected to the flowmeter. The flowmeter responds in 35 ms delay compared to the pressure changes of the flow step from 30 to 60 L/min. The dynamic response for alternative flow change is shown in Fig. 5. The rectangularly flow

changes are given by a four ports valve with 10 ms delay. The flowmeter measures the flow changes of amplitude of ± 35 L/min without the transient instability. Figure 6 shows the pressure loss characteristics of the flowmeter for which working fluid is VG32 at 40 °C.

PROPORTIONAL SEAT VALVE WITH MOMENTUM FLOWMETER

Characteristics of the flow sensing seat valve

The experimental circuit for the flow sensing seat valve with the momentum flowmeter is shown in Fig. 7. The controller calculates the pulse width of PWM rates for the pilot valve. The signal is given by the error between the reference flow rates Q_r

Fig.3 Steady state characteristics of the momentum flowmeter

Fig.4 Transient characteristics of stepped flow rates change

Fig.5 Transient characteristics of alternating flow rates change

Fig.6 Pressure loss of the momentum flowmeter

Fig. 7 Flow control system
(Flow sensing seat valve with load)

Fig. 8 $P_L - Q_L$ characteristics

and the measured flow rates Q_y . In the testing circuit, an variable orifice and the gear flowmeter (KRACHT VLUTRONIC VC1, 1.05cc/pulse) are connected serially for loading the valve and calibrating the flow rates. Figure 8 shows the characteristics of controlled flow rates versus load pressure. The compensation by the flowmeter makes it possible to control the flow rates insensitively against the load pressure change. Figure 9 shows the transient characteristics of the valve without load. The valve controls the stepped flow rate change from 30 to 60 L/min within 80 ms. From Fig.10, we

Fig. 9 Step response (without load)
(Q_r : Command, Q_L : Gear flowmeter)

Fig. 10 Flow control dynamics against
load pressure changes

can see the insensitivity of the valve against load pressure disturbance. The valve controls flow rates within 0.1 s against the stepped load pressure change from 0 to 4 MPa.

Bond graphs

The dynamics of the valve have been simulated analytically by bond graphs. The mathematical model of the flow sensing seat valve is expressed by bond graphs in Fig.11. Figure 12 shows one of simulated results using a ready-published soft ware BGSP⁽⁸⁾. The BGSP simulates a little flow rates change at the pressure change due to the control lag.

CONCLUSION

The proportional seat valve with the momentum flowmeter has been developed. The high-speed switching pilot valve controlled by PWM signals is applied to the operation of the main seat valve. The valve controls the stepped flow rate from 30 to 60 L/min within 0.08 s, and compensates load pressure change of 4 MPa within 0.1 s. The simulations by bond graphs agree with the measured results of the transient flow rates change due to the control lag.

AKNOWLEDGEMENT

Authors would like to thank Mr. Yusaku Nozawa of Hitachi Construction Machinery Co., Ltd. for making the seat valve, and Mr. Kenji Masuda of Daikin Industry for developing the flowmeter.

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Fig.11 Bond graphs for the flow sensing seat valve with load

Fig.12 Simulated results to load pressure changes

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