STATIC CHARACTERISTICS OF RELIEF VALVE WITH PILOT G- π BRIDGE HYDRAULIC RESISTANCES NETWORK

Hu Yanping and Liu Deshun

Department of Mechatronic Engineering

Xiangtan Polytechnic University

Xiangtan, Hunan, P. R. China

(E-mail: Huyan @ xtpu.org.cn)

ABSTRACT

This paper proposes a new construction of the relief valve with pilot G- π bridge hydraulic resistances network. The valve's static characteristics are studied theoretically. The formulas for designing the relief valve with zero static pressure override are obtained. The static performances of the relief valve are experimentally investigated. The theoretical and experimental results show that the relief valve developed in this paper is un-sensitive to flow rate, i.e. when the overflow increases the control pressure is kept constant.

KEYWORDS

Static characteristics, Relief valve, Hydraulic resistances

NOMENCLATURE

a_1	area of main stage poppet seat	[m ²]	c_{d2}	discharge coefficient of pilot poppet	
a_2	area of spring chamber of main stage	[m ²]	D_1	diameter of pilot poppet seat	[m]
a_3	area of piston on pilot poppet	[m ²]	D_2	diameter of main poppet seat	[m]
a_4	a_3 minus area of pilot poppet seat	[m ²]	d_1	diameter of orifice r_1	[m]
c_{d1}	discharge coefficient of main poppet		d_2	diameter of orifice r_2	[m]
			k_x	Main spring stiffness	[N/m]
			k_y	Pilot spring stiffness	[N/m]

k_w	flow force coefficient of main poppet	[m]
L	length of orifice r_1 and r_2	[m]
p_n	full flow pressure of relief valve	[Pa]
p_0	cracking pressure of relief valve	[Pa]
p_1	pressure at inlet of main poppet	[Pa]
p_2	pressure at outlet of resistor r_1	[Pa]
p_3	pressure at inlet of pilot poppet	[Pa]
q	flowrate through inlet tube	[m ³ /s]
q_1	flowrate through resistor r_1	[m ³ /s]
q_2	flowrate through resistor r_2	[m ³ /s]
q_3	flowrate through pilot poppet	[m ³ /s]
q_4	flowrate through main poppet	[m ³ /s]
x	displacement of main poppet valve	[m]
x_L	initial compression of main stage spring	[m]
y	displacement of pilot poppet valve	[m]
y_L	initial compression of pilot stage spring	[m]
ρ	density of oil	[kg/m ³]
μ	dynamic viscosity	[Ns/m ²]
α_1	angle of main poppet face	[°]
α_2	angle of pilot poppet face	[°]
δ_p	pressure uniformity coefficient	

1. INTRODUCTION

The relief valve widely used now is illustrated in Figure 1, its pilot circuit is a B-half bridge hydraulic resistance network. A typical static pressure flowrate characteristic of the relief valve is shown as Figure 2, where p_0 is cracking pressure and p_n is full flow pressure. The pressure override Δp is defined as difference between p_n and p_0 , i.e. $\Delta p = p_n - p_0$. Another parameter by which we can judge the quality of static characteristic of the relief valve is the pressure uniformity coefficient δ_p , which is defined as:

$$\delta_p = \frac{p_n - p_0}{p_n} \times 100\% = \frac{\Delta p}{p_n} \times 100\% \quad (1)$$

The value of δ_p is typically about 10% to 17% for relief valves with B-half bridge pilot hydraulic resistance circuit. Pressure override is caused by the compression of the springs and flow forces across the poppets. In order to reduce pressure override, a direct pressure sensing relief valve shown in Figure 3 was investigated (D.Yao

1997). The feature of the relief valve is that p_1 directly

Figure 1 Schematic of relief valve with B-half bridge pilot circuit

acts on the left end of the pilot valve. The force balancing the pilot spring force is p_1 , instead of p_2 shown

Figure 2 Static characteristic curve of relief valve with B-half bridge

in Figure 1. Although its δ_p is about 4%, and thus it is smaller than δ_p of the valve shown in Figure 1, a positive

Figure 3 Schematic of direct pressure sensing relief valve

pressure override still exists.

A new relief valve designed by authors incorporates three hydraulic resistances r_1 , r_2 and r_3 (Hu Yanping, 1999). As it is shown in Figure 4, hydraulic resistances r_1 and r_2 are fixed resistances and r_3 is a variable resistance. The relief valve with pilot G- π bridge hydraulic

Figure 4 Principle of relief valve with G- π bridge pilot circuit
1.main poppet 2.main spring 3.pilot poppet and piston 4.pilot spring 5.adjust screw

resistances network is proposed in this paper. The static characteristics of the relief valve are studied. The results show that the static pressure override of the relief valve may be positive or zero in terms of pilot hydraulic resistance parameters.

2. THE PRINCIPLE OF NEW RELIEF VALVE

The principle of the relief valve with a pilot G- π bridge hydraulic resistance network is shown in Figure 4. It consists of main valve 1 and pilot valve 3. r_1 and r_2 are fixed hydraulic resistors. The pilot poppet is a variable hydraulic resistor, defined as r_3 in Figure 4.

The principle of the valve operation is as follows. When the force due to the inlet pressure p_1 is less than pilot valve spring force, both main valve and pilot valve are closed. Thus $p_1=p_2=p_3$. When pressure p_1 increases and reaches the cracking pressure of the pilot relief valve, the pilot valve opens. When oil flow to tank via r_1 , r_2 and r_3 ,

there is a pressure drop on resistor r_1 and r_2 . Now $p_3 < p_2 < p_1$. The greater the flowrate through the pilot network is, the larger the pressure drop across r_1 , r_2 and r_3 is. When the force produced by $\Delta p_1 = p_1 - p_3$ is larger than the main spring force, the main valve opens. Oil flows to tank via opening of the main valve. Thus continuous increase of pressure in hydraulic system is limited.

The pressure p_2 acts on the left end of the piston and pressure p_3 acts on the right end of the piston. When p_2 increases, the opening of the pilot relief valve will increase. On the other hand, when p_3 increases, the opening of the pilot valve will be reduced. The rate at which p_2 and p_3 vary will depend on the flow areas of the hydraulic resistors r_1 and r_2 . Therefore, different pressure flowrate characteristics can be obtained by setting different hydraulic resistors.

3. ANALYSIS OF STATIC CHARACTERISTICS OF THE RELIEF VALVE

For the pilot relief valve showed in Figure 4, neglecting flow force on the pilot poppet, flow continuity equation and force equilibrium equation of the valve can be written as follows:

The pressure drop-flowrate equation associated with resistances r_1 , r_2 and r_3 are:

$$q_1 = \frac{\pi d_1^4}{128 \mu L} (p_1 - p_2) = c_1 (p_1 - p_2) \quad (2)$$

$$q_2 = \frac{\pi d_2^4}{128 \mu L} (p_2 - p_3) = c_2 (p_2 - p_3) \quad (3)$$

$$q_3 = c_{d2} \pi D_2 y \sin \alpha_2 \sqrt{2 p_3 / \rho} = b y \sqrt{p_3} \quad (4)$$

The steady state force balance on the pilot poppet is given by

$$p_2 a_3 = p_3 a_4 + k_x (y_l + y) \quad (5)$$

Flowrate equation for the orifice formed by the main poppet:

$$q_4 = c_{d1} \pi D_1 x \sin \alpha_1 \sqrt{2 p_1 / \rho} = b_1 x \sqrt{p_1} \quad (6)$$

The flow continuity equation at the inlet is

$$q = q_1 + q_4 \quad (7)$$

The steady state force balance on the main poppet is given by

$$p_1 a_1 = p_3 a_2 + k_x(x_l + x) + k_w x p_1 \quad (8)$$

Where:

$$c_1 = \frac{\pi d_1^4}{128 \mu L} \quad (9)$$

$$c_2 = \frac{\pi d_2^4}{128 \mu L} \quad (10)$$

$$b = c_{d2} \pi D_2 \sin \alpha_2 \sqrt{2/\rho} \quad (11)$$

$$b_1 = c_{d1} \pi D_1 \sin \alpha_1 \sqrt{2/\rho} \quad (12)$$

When the relief valve works at steady state, obviously $q_1 = q_2 = q_3$. Linearizing Eq. (2)-(8) about steady state points $(p_{10}, p_{20}, p_{30}, q_0, q_{10}, q_{20}, q_{30}, q_{40}, x_0, y_0)$, yields Eq. (13)-(19):

$$\Delta q_1 = d_1 (\Delta p_1 - \Delta p_2) \quad (13)$$

$$\Delta q_1 = d_2 (\Delta p_2 - \Delta p_3) \quad (14)$$

$$\Delta q_1 = d_3 \Delta y + d_4 \Delta p_3 \quad (15)$$

$$\Delta p_2 a_3 = \Delta p_3 a_4 + k \Delta y \quad (16)$$

$$\Delta p_3 = d_5 \Delta p_1 - d_6 \Delta x \quad (17)$$

$$\Delta q_4 = d_7 \Delta p_1 + d_8 \Delta x \quad (18)$$

$$\Delta q = \Delta q_1 + \Delta q_4 \quad (19)$$

where:

$$d_1 = c_1 \quad (20)$$

$$d_2 = c_2 \quad (21)$$

$$d_3 = b \sqrt{p_{30}} = \frac{q_{10}}{y_0} \quad (22)$$

$$d_4 = \frac{0.5 b y_0}{\sqrt{p_{30}}} = \frac{0.5 b^2 y_0^2}{q_{10}} \quad (23)$$

$$d_5 = \frac{a_1 - k_w x_0}{a_2} \quad (24)$$

$$d_6 = \frac{k_x + k_w p_{10}}{a_2} \quad (25)$$

$$d_7 = \frac{0.5 b_1 x_0}{\sqrt{p_{10}}} = \frac{0.5 b_1^2 x_0^2}{q_{40}} \quad (26)$$

$$d_8 = b_1 \sqrt{p_{10}} = \frac{q_{40}}{x_0} \quad (27)$$

By solving the above coupling equations, the following relationship is derived

$$\Delta p_1 = e \Delta q \quad (28)$$

where:

$$e = \frac{d_6 e_2}{d_6 + d_6 d_7 e_2 + d_5 d_8 e_2 - d_8 e_1} \quad (29)$$

$$e_1 = \frac{k_y d_2 - a_3 d_3}{e_3} \quad (30)$$

$$e_2 = \frac{e_3 + k_y d_1 d_2 + k_y d_1 d_4 - a_4 d_1 d_3}{d_1 e_3} \quad (31)$$

$$e_3 = d_2 d_3 (a_3 - a_4) + k_y d_2 d_4 \quad (32)$$

The value of coefficient e determines the pressure flowrate characteristics of the relief valve. For the conventional relief valve, the value of coefficient e is always positive. but the value of coefficient e may be positive or zero for the relief valve studied in this paper. Thus, the relief valve has two different kinds of pressure-flowrate characteristics.

(1) $e > 0$, control pressure p_1 increases with increasing inlet flow.

(2) $e = 0$, control pressure p_1 keeps constant with increasing inlet flow.

In Eq. (29), the value of denominator is larger than zero and the value of d_6 is positive. For $e = 0$, e_2 must be zero.

Therefore :

$$e_2 = \frac{e_3 + k_y d_1 d_2 + k_y d_1 d_4 - a_4 d_1 d_3}{d_1 e_3} = 0 \quad (33)$$

Because values of e_3 and d_1 are positive, Eq.(33) becomes:

$$e_3 + k_y d_1 d_2 + k_y d_1 d_4 - a_4 d_1 d_3 = 0 \quad (34)$$

By substituting Eq.(32) into Eq.(34), the Eq.(34) becomes:

$$d_2 d_3 a_3 - (d_3 a_4 - k_y d_4)(d_1 + d_2) + k_y d_1 d_2 = 0 \quad (35)$$

By substituting Eq.(20), (21), (22), (23) into Eq.(35) and noting $q_{10}=q_{20}=q_{30}$, The following quadratic equation results:

$$2a_3c_2q_{10}^2 - 2a_4(c_1 + c_2)q_{10}^2 + 2k_y c_1 c_2 y_0 q_{10} + k_y(c_1 + c_2)b^2 y_0^3 = 0 \quad (36)$$

Eq.(36) only contains parameters of the pilot circuit of the relief valve. It doesn't contain parameters of the main valve.

It can be shown that the value of fourth term $k_y(c_1 + c_2)b^2 y_0^3$ in Eq.(36) is small compared to the other terms. Thus Eq.(36) reduces to

$$a_3c_2q_{10} - a_4(c_1 + c_2)q_{10} + k_y c_1 c_2 y_0 = 0 \quad (37)$$

or

$$a_3c_2 - a_4(c_1 + c_2) + k_y c_1 c_2 / (b\sqrt{p_{30}}) = 0 \quad (38)$$

Let

$$\Delta = a_3c_2 - a_4(c_1 + c_2) + k_y c_1 c_2 / (b\sqrt{p_{30}}) \quad (39)$$

Equation (37) is the formula of the relief valve which has zero static pressure override. It shows that main parameters which determine the different pressure-flowrate characteristics of the relief valve are: diameters of the hydraulic resistance r_1 , r_2 , the pilot valve spring stiffness k_y and left area a_3 and middle area a_4 .

4. EXPERIMENTS OF THE STATIC CHARACTERISTICS OF THE RELIEF VALVE

The main parametric data of the test relief valve is illustrated in table 1 and table 2.

Experimental results are shown in Figure 5. Only the diameter of r_2 is changed, other parameters are same for all experiments in Figure 5. When Δ is positive, override of relief valve is also positive (Figure 5a~5c), When Δ is

Table 1 Parametric data of the test relief valve

a_1	3.14×10^{-4}	α_1	18.5°
a_2	3.80×10^{-4}	α_2	35°
a_3	5.03×10^{-5}	b	0.146×10^{-3}
a_4	3.06×10^{-5}	μ	2.7×10^{-2}
k_x	6.47×10^3	ρ	900
k_y	4.52×10^5	c_1	1.82×10^{-10}
L	5×10^{-3}	c_{d1}	0.62
x_L	1.66×10^{-2}	c_{d2}	0.62
y_L	0.87×10^{-3}		

Table 2 Parametric data of resistor r_2 and Δ

d_{r2}	c_2	Δ
1.2×10^{-3}	3.77×10^{-10}	2.74×10^{-14}
1.0×10^{-3}	1.82×10^{-10}	1.03×10^{-14}
0.8×10^{-3}	0.75×10^{-10}	0.1×10^{-14}
0.7×10^{-3}	0.44×10^{-10}	-0.18×10^{-14}

almost zero, the override of relief valve is almost zero (Figure 5d). Therefore the steady state experimental results are in good agreement with analysis.

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Figure 5a

Figure 5c

Figure 5b

Figure 5d

Figure 5 Experimental curves