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Design of pilot-assisted load control valve for proportional flow control and fast opening performance based on dynamics modeling

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ABSTRACT

This paper presents a flow control performance design method of pilot-assisted load control valve (LCV) based on dynamics modeling. Good flow control performance has both static and dynamic aspects for an LCV. In static aspect, proportional flow control is required, which means the static flow through the valve can be proportionally controlled by pilot pressure. In dynamic aspect, fast opening performance is required, which means the desired flow can be fast provided but without overshoot when given a step pilot pressure. Good flow control performance of an LCV is the key to improve the system performance and to reduce the system complexity. In the method proposed by this paper, a static model of the static flow control performance based on hydraulic half bridge analysis was built to determine the area-displacement features of two key orifices to achieve proportional flow control. In addition, a dynamic model of the spool motions was provided to study the compensation orifice effect on the opening performance of the valve and further to determine the optimized orifice size. An actual LCV was developed according to above method. Tests were carried out both on a mobile crane and a test rig to validate its static and dynamic flow control performance, respectively. The good flow control performance of the valve in the tests indicates that the proposed method can provide theoretical guidance for pilot-assisted LCV design.

1. Introduction

Hydraulic valves, which are widely applied to control high power fluid flow with relatively small force, play key roles in hydraulic systems for many applications [1,2]. Load control valves (LCVs) are commonly applied in hydraulic systems with negative loads, for example in booming and lifting systems of cranes [3]. LCV develops from the general concept of counterbalance valve (CBV), while LCVs have an additional ability of flow control when lowering the load. In hydraulic systems with negative loads, LCVs play compound roles of a check valve and a pilot throttle valve, including holding the load, restricting oil from a hydraulic cylinder or motor to prevent cavitation and controlling the lowering speed of the load [4].

Good flow control performance has both static and dynamic aspects for an LCV. In static aspect, proportional flow control is required, which means the static flow through the valve can be proportionally controlled by pilot pressure. In dynamic aspect, fast opening performance is required, which means the desired flow can be fast provided but without overshoot when given a step pilot pressure. Good flow control performance of an LCV is the key to improve the system performance and to reduce the system complexity. An LCV with proportional flow control performance plays the role of controlling the lowering speed of negative load instead of a proportional directional control valve or multi-way valve. Therefore, it will simplify system complexity and help reduce energy consumption [5–7]. Good dynamic flow control performance (fast but without overshoot) is also important to LCV, especially for the safety during the lowering action. That is because big overshoot of the flow of the opening operation will cause an excessive speed and may lead to accidents in some situations. In addition, the opening performance of an LCV commonly affects the stability of the whole system [8–11]. If the system is load sensitive, the stability problem may become worse due to serious overshoot in LCV [12].

Traditional systems commonly employ CBVs for negative load holding. While for the lowering speed control, an additional throttle valve or proportional directional control valve has to be added to the system, making the system more complex and introducing the problem of instability. CBVs commonly employ pressure–spring balance principle, which employs the pilot pressure force to push a high stiffness spring for the purpose of controlling the opening and closing of the main orifice [13–15]. To realize a better opening performance, high pilot pressure is commonly required, which results in additional energy consumption [7]. To improve the system stabil-

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Nomenclature

c	Discharge coefficient
f_{ms}	Coulomb friction of main spool
f_{ps}	Coulomb friction of pilot spool assembly
k_C	Stiffness of the control spring
k_F	Stiffness of the feedback spring
m_{ms}	Mass of the main spool
m_{ps}	Mass of the pilot spool assembly
p_B	Pressure at port B
p_C	pPressure of chamber C
p_D	Pressure of chamber D
p_X	Pilot pressure
x_{ps}	Displacement of the pilot spool
x_{ms}	Displacement of the main spool
A_{pp}	Area of the pilot piston
A_1	Bigger end face area of the pilot spool
A_2	Smaller end face area of the main spool
A_3	Bigger end face area of the main spool
A_C	Metering area of compensation orifice
A'_P	Metering area of the equivalent pilot orifice
A_r	Smaller end face area of the pilot spool
A_F	Metering area of feedback orifice
A_{FC}	Metering area of fast close orifice
A_M	Metering area of main orifice
CBV	Counterbalance valve
D_{ms}	Viscous friction coefficient of main spool
D_{ps}	Viscous friction coefficient of pilot spool assembly
E	Bulk modulus of oil
F_{fs}	Force of the feedback spring
F_{C0}	Initial force of the control spring
F_{F0}	Initial force of the feedback spring
LCV	Load control valve
Q_F	Flow rate through feedback orifice
Q_{FC}	Flow rate through fast close orifice
Q_C	Flow rate through compensation orifice
Q_M	Flow rate through main orifice
V_{C0}	Initial volume of chamber C
V_{D0}	Initial volume of chamber D

Symbols

ρ	Oil density
δ	Area ratio

ity and save the energy consumption, some improvement work has been done by Andersson through implementing new designs for the pressure–spring balance based CBV [16]. However, it is still difficult to realize proportional flow control even through the improved method [16].

To overcome the disadvantages of traditional CBVs, a novel pressure–pressure balance principle was proposed by researchers [17–19]. Because flow control ability is added to the valves, they are named LCVs to illustrate this advantage compared with traditional CBVs. The pressure–pressure balance principle is the way that employs the pilot pressure to control the motion of a pilot spool, which will affect one end chamber pressure of the main spool. Different from the pressure–spring balance principle, the main spool of this principle moves according to the pressure difference exerted on its two end chambers [17]. As a result, low stiffness spring can be used in the LCV, which only provides a function of helping the main spool close. Above principle provides the possibility to realize both proportional flow control and fast opening performance for LCVs.

Some patents have been published to introduce the designs of pressure–pressure balance based LCVs [18,19]. Both the designs from Haussler et al. [18] and Xie et al. [19] employed hydraulic half bridges to control the movements of main spools. The two orifices forming a half bridge and making the LCVs have proportional flow control performance were separately designed onto the pilot spool and main spool. To gain an opening performance without overshoot, they introduced an additional compensation orifice to the pilot spool. But upon now, the design of the two orifices making up the hydraulic half bridge and the optimization of the compensation orifice parameter still highly depend on experiment trial and engineering experience. It is necessary to conduct targeted theoretical analysis of the hydraulic half bridge and the compensation orifice effect to give guidance for flow control performance design of LCVs.

This paper aims at providing theoretical guidance to the design of LCVs for good flow control performance through dynamics modeling. The advantage of the here discussed design method is to save the cost and time to build and test prototypes with different parameters to get the final design. The test results of the real valve built according to the optimized parameters come out as designed. The contents of the present paper are as follows: building a static model of the static flow control performance of the LCV and investigating the area-displacement features of the orifices to achieve proportional flow control; building the dynamic model of spool motions and analyzing the parameter of the compensation orifice to obtain a fast opening performance without overshoot; finally, an actual LCV was developed according to above method. Tests were carried out both on a mobile crane and on a test rig to validate its static and dynamic flow control performance, respectively. The good flow control performance of the valve in the tests indicates that the proposed method can provide theoretical guidance for LCV design.

2. Static model of static flow control performance and design of area-displacement features for orifices

An LCV proposed by us in Ref. [19] with the sectional structure and circuit diagram illustrated in Fig. 1 is taken as an example to present the model of the static flow control performance and the design of the area-displacement features for two key orifices. It consists of a pilot piston, a control spring, a feedback spring, a pilot spool, a main spool etc. There are four ports on the valve: A is the back flow port, B is the load port (usually mounted to a hydraulic cylinder or motor directly without any hose), X is the pilot port to control the valve and L is a drain port. In addition, the ratios of the sizes of the components have been changed and some structures have been simplified to illustrate the important details of the valve and to make the figure clear.

Typical application and the valve operations when lifting and lowering the load are illustrated in Fig. 2. As shown in the figure, for lifting up operation, the directional control valve is operated to its right position and the LCV works as a check valve. High pressure oil of port A pushes the main spool, compresses the feedback spring, and opens the main orifice. As a result, the oil goes out through port B and then flows into the non-rod chamber of the cylinder to drive the load up. The oil flow is marked by arrows in the operation figure. As low stiffness feedback spring is used, the cracking pressure of the LCV is very low. For lowering down operation, the directional control valve is operated to its left position. The pilot piston of the LCV is driven by the pilot pressure of port X and then pushes the pilot spool to open. Consequently, the oil in the feedback spring chamber (named as chamber C for short) goes through the compensation orifice and the pilot orifice to the drain port. As long as the pressure of the chamber C decreases to a certain level, the force balance of the main spool is interrupted, the main spool moves due to the force of the high pressure oil of port B, the main