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Realization of direct flow control with load pressure compensation on a load control valve applied in overrunning load hydraulic systems

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ABSTRACT

This paper presents the realization of direct proportional flow control with load pressure compensation feature on a LCV (load control valve). Proportional flow control performance means the flow through the LCV is proportional to the pilot pressure in the control stroke. Proportional flow control decides the overrunning load lowering speed control performance of the whole system. The load pressure compensation feature means when the load pressure is too high, the flow of the LCV can be restricted about the maximum rated flow. The load pressure compensation feature is important to the safety of the system. That is because large flow means undesired fast lowering speed, which will cause accident in applications, especially those large mass overrunning load systems. In this paper, the flow control performance was simulated and the parameter relationship of the orifices was derived, which is the base for the optimizing of the compensation orifice. In addition, load pressure compensation feature was simulated and the compensation orifice size was optimized. Finally, an LCV built according to above methods was tested on a test rig. Experiment data validates the methods presented and the realization of direct flow control with load pressure compensation feature gives guidance for the direct flow control performance development of other valves.

1. Introduction

Direct flow control performance, which means controlling the flow through a valve without any external feedback component like a flow meter etc., is very important for many hydraulic valves or system applications [1]. Much work including vibrations induced by high speed flow, hysteresis caused by radical unbalanced force worked on the spool, cavitation induced by poor orifice design etc. has been done to develop the direct flow control performance of varies of hydraulic valves [2–4].

In the research field of load control valve (LCV), the developing of direct flow control performance is also very important and has drawn the interest of many researchers. LCV are used widely in overrunning load hydraulic systems to counterbalance the load pressure caused by the load gravity when there is no action and to control the load speed when lowering the overrunning load [5]. Controlling the speed means controlling the oil flow in hydraulic systems and usually there is no flow meter to give flow feedback for the LCV. The action performance of lowering the overrunning load is mostly cared by the designers and users of these systems, so the direct flow control performance of the LCV is the key to overrunning hydraulic systems. In addition, the action of lowering the overrunning load is often involved with the problem of safety, so the LCV is often directly mounted on the hydraulic actuator (hydraulic cylinder or motor). During the action of elevating the load, LCV only acts as a low cracking pressure crack valve and the elevating speed is usually controlled by another directional valve or throttle valve.

The direct flow control performance of LCV contains two major problems, which are proportional flow control and load pressure compensation. Proportional flow control performance means the flow through the LCV is proportional to the pilot pressure in the control stroke. As mentioned above, proportional flow control decides the overrunning load lowering speed control performance of the whole system. The load pressure compensation feature means when the load pressure is high, the flow of the LCV can be restricted about the maximum rated flow. The load pressure compensation feature is important to the safety of the system because large flow means undesired fast lowering speed and fast lowering speed will cause accident in applications, especially those large mass overrunning load systems.

For better proportional flow control performance of LCV, much work has been done but the flow control performance can not be developed much because the working principle restriction. Traditional LCVs are often single-stage, employing the pressure-spring balance principle. The pilot pressure directly overcomes a

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Nomenclature

A_{pp}	pilot piston area
A_r	smaller end face area of pilot spool
A_3	bigger end face area of main spool
p_D	pressure of chamber D
x_{ps}	displacement of pilot spool
p_C	pressure of chamber C
k_F	stiffness of the feedback spring
x_{ms}	displacement of main spool
f_{ms}	coulomb friction of main spool
A_P	metering area of pilot orifice
A_C	metering area of compensation orifice
A_{FC}	metering area of fast close orifice
F_{fs}	spring force of feedback spring
n_P	number of pilot orifice
β	angle marked in Fig. 4.
θ	angle of pilot orifice
w	width of feedback orifice
γ	angle of feedback orifice
F_0	initial force of feedback spring
Q_F	feedback orifice flow rate
Q_C	compensation orifice flow rate
E	bulk modulus of hydraulic oil
A_1	bigger end face area of pilot spool
A_2	smaller end face area of main spool
p_X	pressure of port X
m_{ps}	mass of pilot spool assembly
f_{ps}	coulomb friction of pilot spool assembly
D_{ps}	viscous friction coefficient of pilot spool assembly
D_{ms}	viscous friction coefficient of main spool
m_{ms}	mass of main spool
p_B	pressure of port B
A'_P	metering area of equivalent pilot orifice
A_F	metering area of feedback orifice
c	discharge coefficient
ρ	hydraulic oil density
x_0	overlap of pilot orifice
r	radius of pilot spool
α	angle marked in Fig. 4.
n_F	number of feedback orifice
h_0	initial depth of feedback orifice
V_C	initial volume of chamber C
Q_{FC}	fast close orifice flow rate
V_D	initial volume of chamber D
LCV	load control valve

high stiffness spring to open the spool. Because of the high stiffness spring, the pilot pressure is always very high and the spool stroke of traditional LCVs are always short. The short control stroke is the key problem that restricts the developing of the flow control performance. In addition, the high pilot pressure tends to cause high energy consumption. Research has been done to develop the energy consumption problem but the flow control performance improves little [6].

Other researchers proposed novel principles to build pressure-pressure balance based LCVs for the purpose of overcoming the problems of traditional LCVs. The pressure-pressure balance based LCVs are two-stage, employing a pilot spool to control the end chamber pressure of the main spool. The pilot pressure works on the pilot spool instead of a high stiffness spring. Different control circuits of the pilot spool have been proposed to control the displacement of main spool by Haussler [7] and Xie [8]. The principle allows long stroke and low stiffness spring of the main spool. As a result, the proportional flow control performance of the LCV has been improved greatly.

Many researches have been investigated for load pressure compensation feature of other valves [9] but little work on improving the LCV load pressure compensation feature has been published [10]. A pressure compensator is used to achieve load pressure compensation on a directional control valve to maintain the flow through the valve as constant as possible as the load pressure changes [11]. Flow forces are employed to achieve load pressure compensation on a proportional directional valve in the research of Lisowski [12]. A hydraulic-feedback proportional valve is designed by Liu to achieve load pressure compensation in the application of construction machinery [13]. Different from these former researches, a compensation orifice is introduced in this paper to the proposed LCV to realize load pressure compensation feature. The compensation orifice introduces additional pressure difference force to the pilot spool, which will lead to the displacement decrease of the pilot spool. As, a result, the force balance of the main spool will also be affected by the moving of pilot spool, making sure the flow through the valve is restricted about the maximum rated flow.

This paper provides the analyzing and optimizing method for direct proportional flow control with load pressure compensation feature on a load control valve. The contents of this paper are as follows: Introducing the working principle of the proposed LCV and how load compensation is realized; simulating the flow control performance and deriving the parameter relationship of the orifices, which is the base for the optimizing of the compensation orifice; modeling of the load pressure compensation feature and optimizing of the compensation orifice size; finally, an LCV built according above methods was tested on a test rig. Experiment data validates above methods and the realization of direct flow control with load pressure compensation feature gives guidance for the direct flow control performance development of other valves.

2. Working principle of the LCV and realization of load compensation

The sectional structure of the proposed LCV is illustrated in Fig. 1. As is shown in the figure, the valve is consisted of a main spool, a pilot spool, a pilot piston, two springs etc. To make the figure easy to read, we simplified the other structures such as the spool seats and the scale was modified to illustrate the details of the pilot spool. The LCV's four ports named as A, B, L and X are the back flow port, the load port, the drain port and the pilot port separately. Usually in the applications of the LCV, port B is mounted directly on a hydraulic actuator (cylinder or motor) to counterbalance the overrunning load and to ensure safety in case of hose corruption; port A is connected to directional valve or directly to oil tank; port L is a drain port and port X is often connected to the other side of the hydraulic actuator or separately controlled by an operation lever etc.

To give a detailed description of how the LCV works in the operations, a typical application of the proposed LCV in the hydraulic winch system is presented in Fig. 2. As is shown in the figure, a hydraulic motor is employed to drive the winding drum, which can elevating or lowering the load in two rotating directions. A hydraulic pump is used to give high pressure oil and a directional control valve is needed to decide whether to elevate or lower the load. The proposed LCV is used to counterbalance the load pressure produced by the gravity of the load when there is no