DEVELOPMENT OF HYDRAULIC FAST SWITCHING VALVES WITH HIGHLY BALANCED VALVING ELEMENTS

By

Adham Ibrahim Hassan Hosni

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in

Mechanical Design and Production Engineering

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
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Title of Thesis:

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Key Words:
Valve, hydraulic, fast switching, directional control

Summary:
Fast switching hydraulic control valves can be realized when the required stroking forces and displacements of the valving elements, whether poppets or spools, are small enough to cope with the capabilities of compact actuating devices. A new class of valves are proposed and analyzed in this work, in which the valving elements are subjected to the high inlet pressure on both sides that have small area difference. This would result in reducing both the required driving forces and the strength needs of these valving elements. The return of the valving elements to their initial positions in this case results from the small pressure and flow forces unbalance only, or with the assistance of an additional spring force. A valve design with long control edge is developed to allow obtaining appreciable large control orifice area from a small valving element displacement, and hence a high flow gain is realized. The small valving element displacement reduces the demands imposed on the actuating devices and allows the use of piezoelectric actuators of short stroke or electromagnetic driving devices that generate high forces at narrow gaps and reasonable ampere-turn values. The configurations of the proposed fast switching valves well fit the requirements of the Pulse Width Modulation control techniques. Examples of using the proposed valves as 3/2 and 2/2 directional control valves are shown, and the flow gain and forces acting on the valving elements for a valve size NG 6 are numerically evaluated. The same concept is applicable for valves of larger sizes. The evaluated flow gain is comparable with that of the conventional directional control valves of the same and even larger sizes.

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Dedication

To my wonderful parents, wife, and my little Abd El Rahman & Retal.

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Nomenclature

CAD	Computer Aided Design
CFD	Computational fluid dynamics
FEA	Finite element analysis
DFCU	Digital flow control unit
DGCVs	Digitally controlled valves
DHPMS	Digital hydraulic power management system
OPM	Optimized pulse modulation technique
PFM	Pulse frequency modulation
PWM	Pulse-width modulation
C_b	Damping coefficient
E	Piezoelectric actuator max displacement
F_s	Spool flow forces
F_p	Piezoelectric actuator force
I_b	Mass moment of inertia of the lever about its fulcrum
L	Control lever length
K_p	Piezoelectric stiffness, from the specs sheet
m_s	Mass of the spool
μ	Oil dynamic viscosity
x_s	Spool displacement
x_p	Piezoelectric actuator initial displacement
θ	Slope angel of the control lever
y	Deflection at the end of the lever
φ	Angular deflection

Abstract

Fast switching hydraulic control valves can be realized when the required stroking forces and displacements of the valving elements, whether poppets or spools, are small enough to cope with the capabilities of compact actuating devices. A new class of valves are proposed and analyzed in this work, in which the valving elements are subjected to the high inlet pressure on both sides that have small area difference. This would result in reducing both the required driving forces and the strength needs of these valving elements. The return of the valving elements to their initial positions in this case results from the small pressure and flow forces unbalance only, or with the assistance of an additional spring force. A valve design with long control edge is developed to allow obtaining appreciable large control orifice area from a small valving element displacement, and hence a high flow gain is realized. The small valving element displacement reduces the demands imposed on the actuating devices and allows the use of piezoelectric actuators of short stroke or electromagnetic driving devices that generate high forces at narrow gaps and reasonable ampere-turn values. The configurations of the proposed fast switching valves well fit the requirements of the Pulse Width Modulation control techniques. Examples of using the proposed valves as 3/2 and 2/2 directional control valves are shown, and the flow gain and forces acting on the valving elements for a valve size NG 6 are numerically evaluated. The same concept is applicable for valves of larger sizes. The evaluated flow gain is comparable with that of the conventional directional control valves of the same and even larger sizes. Four 2/2 fast switching valves of the proposed design can be assembled in one housing to control the connections between the ports of four way valves independently for highest efficiency and minimum number of control pulses. Using the proposed valves as pilot valves, they provide a low cost technique for upgrading conventional valves to fast switching valves.

If controlled by a proportional electromagnetic device or an adjustable spring, the valve can be designed to operate as a proportional relief or reducing valve. A dynamic mathematical model for the valve has been derived. Matlab SIMULINK software package has been used to simulate the dynamic performance of the valve. The simulation results showed that the valve has a higher speed of response when compared with a servo valve of the same capacity.

Chapter 1: Introduction

Hydraulic power systems are widely used for mechanical power transmission and motion control in stationary industrial systems and in mobile equipment, since they provide in many cases high power density and accurate control compared to the other power transmission systems. These systems consist of generators of hydraulic power; i.e. pumps, control valves and actuators such as cylinders and rotating motors, beside the accessories that are used to condition and filter the liquid that acts as the energy carrying medium.

Control valves are used to direct the liquid flow and control both of its flow rate and pressure in order to control the directions of motion, speeds, and forces of the actuators.

In hydraulic systems the high efficiencies of the current pumps and actuators, amounting in some cases to 95%, do not lead in most cases to hydraulic systems of high efficiency. The main reason for this is the throttling actions, associated with considerable losses, necessary for operation and control of the actuators. These throttling actions are included in the currently available ordinary on/off directional control valves, flow control valves, proportional and servo valves. During the last decade, digital fluid power technology has been introduced and it is currently under considerable research to be used for improving the hydraulic systems efficiency.

1.1 Digital fluid power systems

In digital fluid power technology, valves with throttling actions are replaced by digitally controlled valves (DGCVs), the control software determines the characteristics of the DGCVs instead of the element type, and displacement in on/off and analogue valves [1]. With DGCVs, new solutions are possible through new components and technologies, such as switching converters and digital hydraulic power management system (DHPMS). Beside being of high efficiency, digital fluid power systems are considered, according to [1], [2], and [3], to be robust, with simple and reliable components, of better performance because of faster valves, and of higher degree of flexibility and programmability when compared to analogue systems. On the other hand, challenges face these systems, which include among other things, the expected noise and pressure pulsations as well as the durability and lifetime issues.

Two fundamental branches of digital fluid power systems exist; systems based on parallel connection of several on/off valves as shown in figure 1.1, and systems based on switching technologies as shown in figure 1.2. Both can be applied in different ways.

Two-way on/off valves are generally used in this technology, but in some cases three or four-way valves are also used in order to reduce the number of components in the system.

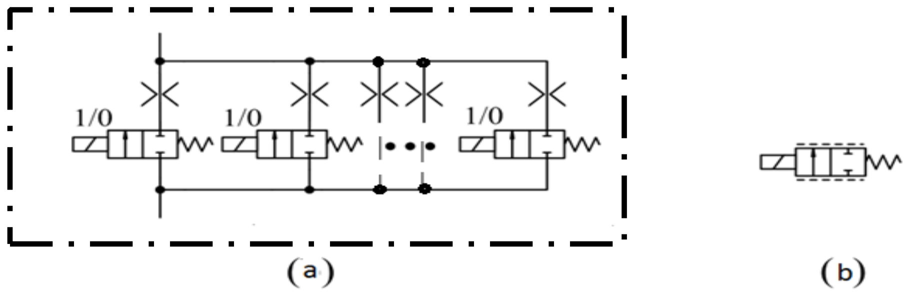

Figure 1.1: Digital flow control unit (a) Detailed symbol

(b) Simplified symbol [1]

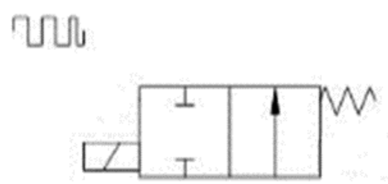

Figure 1.2: Switching controlled on a two-way valve [1]

In the system of parallel connected on/off valves shown in Figure 1.1, a digital flow control unit (DFCU) consisting of several 2/2 and throttle valves is used. The output of this unit is controlled by changing the state combination of the 2/2 valves, and the flow rate of the unit is equal to the sum of the flow rates of the actuated valves. Two factors determine the steady-state characteristics of the DFCU, the number of parallel-connected valves (N) and the relative flow capacities of the valves. Binary coding is the most common method and the flow capacities are in ratios of 1:2:4:8 etc. Independently of the coding, (DFCU) has 2^N opening combinations, which are called states of DFCU. Each state has different flow area in the binary coding. In general, any valve of the DFCU does not require any switchings of its input signal to maintain any of the opening values. Switchings are needed only when the state changes [1].