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Review of energy efficient direct pump controlled cylinder electro-hydraulic technology

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ABSTRACT

Hydraulic cylinder is an indispensable linear actuator in high power applications like construction machinery. In order to reduce the energy consumption, the noise and the waste oil disposal pollution of the hydraulic cylinder control system, the most direct method is adopting the direct pump control technology which eliminates the throttle losses in the main power line. In such system, by changing the speed or the displacement of the pump, the pressure and volume flow will be matched with the need of loads. To date, research works in this field have been reported in many articles, but they are scattered and written in different languages. An overview which can summarize the latest development of this technology appears to be necessary. This paper provides a comprehensive review on this technology, aiming at clarifying recent advances and outlining potential challenges in the research and application of this technology. The review mainly covers three parts: system structure, control, and derived energy recovery system. Also the evolvement of the electro-hydraulic cylinder control system is introduced. The review indicates that attentions should be paid to the control and energy recovery plan of the direct pump controlled cylinder system, and to the newly proposed asymmetric pump controlled differential cylinder technology. It is envisaged that the information gathered in this paper will be a valuable one-stop source of information for researchers, as well as providing a direction for future research in this area.

Contents

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1. Introduction

Electro-hydraulic system as one of the fundamental components has been applied in many equipments, such as the construction machines, the agricultural machines, and the aeroplanes. Common to these applications is that high power is often required to perform the desired work, for example moving material or lifting heavy weights. The power for such drives is often generated by a centralized source, usually an internal combustion engine or a high power electric machine. Using fluid power systems the power is easily distributed via hydraulic lines to either linear or rotary drives. It is estimated that by the year of 2000, the world market of electro-hydraulics is about 30–35 billion dollars per year, and is in steady growth. Meanwhile, energy saving concerns for hydraulic system has been raised with the numerical application of heavy equipments. Electro-hydraulic system mounted equipments often work around the clock and output high power in handling heavy loads. The energy consumption and the waste gas emission of such systems therefore stay high. Take one of the most popular construction machines, 20-t load sensing controlled hydraulic excavator as an example. Such type excavator usually requires a diesel engine of more than 110 kW, which consumes at least 33litre fuel in an hour. The amount of NO_X and CO emitted by this machine is considerable. But only 30% of the consumed energy is used in moving loads. While more than 60% of the energy is consumed in power losses and driving of hydraulic systems [1]. Therefore even a small improvement in the hydraulic system efficiency will have a significant impact on the total energy efficiency of the machine.

Previously, several literature reviews have been presented regarding the application of electro-hydraulic technology in various fields for energy saving purpose. Zhang et al. overviewed the application of hydraulic cylinder based wave energy generation in China [2]. [3,4] reviewed the high pressure hydrostatic technology in energy efficient food production and processing. And the status of hybrid construction machinery, one of the most important application fields of the electro-hydraulic technology, was overviewed in Ref. [5]. Above papers have presented the importance of electro-hydraulic technology in energy saving or generation applications, but the latest development of electro-hydraulic circuit and control technology has not been reviewed. Based on the type of the actuator, such technology can be classified as two types: rotary motion control, i.e. hydraulic pump/motor, and linear motion control, i.e. hydraulic cylinder. Hydraulic rotary motion control is usually implemented in applications like the slewing system and the walking system of construction machines and some low power applications. The control of the hydraulic pump/motor is simple due to the symmetric distribution of the pressure in the system. The hydraulic cylinder has attracted more attention and has gained widely applications. Compared with electromechanical linear actuator and pneumatic cylinder, the high output force of the hydraulic cylinder system makes it indispensable in high power linear motion applications like press machine, bending machine, construction machine, short distance lifting equipment, etc., making the hydraulic cylinder the most emblematic actuator in electro-hydraulic systems. But hydraulic cylinder control system also faces limitations. The energy efficiency of hydraulic control system is lower than that of the electromechanical system and pneumatic system. And the controllability is also poor due to the significant nonlinearity and asymmetric of the system, especially in the differential cylinder control system. The poor energy efficiency and control performance of the cylinder control system significantly undermined the performance of the overall equipments. So over the past decades, efforts have been focused on improving the energy efficiency and control performance of the hydraulic cylinder control system in terms of modifying the system structure and implementing advanced control approaches.

In this paper, state of the art of the pump controlled cylinder technology will be reviewed. First the evolvement of cylinder control system is presented to introduce the advantage of the pump control technology. Then the direct pump controlled double rods cylinder technology and direct pump controlled differential cylinder technology are overviewed respectively in Sections 3 and 4. Existing control strategies for pump controlled cylinder system will be reviewed in Section 5. And the energy recovery technology based on the pump controlled cylinder is also discussed in Section 6. In the end the major challenges that this technology faces will be summarized. The aim of this review is to provide a comprehensive perspective on the challenges and tendency of this technology for the researchers and help them seeking breakthroughs for hydraulic system.

2. Evolvement of hydraulic cylinder control system

Based on the circuit types, hydraulic cylinder control system can be classified as valve controlled system and pump controlled system. Valve controlled hydraulic systems have been widely applied in conventional equipments and machines implement due to its low cost and simple structure. However it faces an obvious drawback, the enormous energy loss, i.e. throttling loss at the control valves [6,7]. Study on the energy analysis of fluid power system has shown that 35% of the input energy of a valve controlled system is consumed in controlling valves. Such poor energy efficiency will lead to the high engine installed power and will generate great amounts of heat during the operation of the equipment. And overheat is also a significant reason that causes breakdown of the machines. To decrease the temperature of the system, additional cooling system is required but it will also further increase the cost and the installed power of the equipments. And as an open circuit, valve controlled system usually needs large amount of hydraulic oil for the operation of the circuit, which to some extent increases the cost of the system and raises pollution problem when disposing the oil. Although the development of load sensing technique effectively reduces the throttling loss of the control valve, eliminating of such loss in valve controlled system is impossible.

Another type of hydraulic system is pump controlled system. Such system falls into two types, open circuit as shown in Fig. 1 (a) and (b) and closed circuit which is also called direct pump controlled system, as shown in Fig. 1(c) and (d). In open circuit pump controlled systems, control valves still place important roles in controlling the flow direction of the oil in the chambers of the cylinder, so the energy efficiency of the system is directly affected by the efficiency of the valves. Some schemes still need throttling valves in the main power lines. And due to the throttling losses in the control valves and pressure losses, the energy efficiency of the open circuit system is degraded.

In order to eliminate the throttling loss and reduce the overall energy consumption of hydraulic system, direct pump controlled system was proposed. As can be seen from Fig. 1(c) and (d), pump controlled cylinder system, different from valve controlled system, is a closed-control structure, in which both chambers of the cylinder are connected with the pump. The primary power sources of these systems are usually electric machines. Compared with the valve controlled system and open circuit pump controlled system, the closed pump controlled system, which does not need control valves, suffers no throttling loss in the main power lines and needs less hydraulic fluid, i.e. oil, in the operation. And based on the pump controlled system, energy recovery solutions for kinetic energy and potential energy are possible. Hence the installed