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Performance analysis of an energy-efficient variable supply pressure electro-hydraulic motion control system ☆

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ABSTRACT

The electro-hydraulic motion control is implemented in diverse applications due to its high power density and good controllability. For a multi-axis system with a single power source, the conventional fixed supply pressure valve-controlled (FPVC) system is a simple but inefficient method due to its dissipating energy via the throttling valves. In this paper, a load-prediction based energy-efficient variable supply pressure valve-controlled (VPVC) method was introduced and implemented on a two-axis robotic arm system. The VPVC system adopts a fixed capacity pump driven by a brushless servomotor. The feed forward part of the VPVC controller predicts the minimum required supply pressure of the system by assuming the control valve of the highest load branch fully open. It is based on the prediction of the required actuation force for a given motion demand, by applying Lagrange's equations of the-second-kind. The feedback control of VPVC is classic proportional (integral) control for the control valves and the motor speed, with measured actuator positions as the feedback signals. Although the VPVC algorithm was demonstrated for a two-axis robotic arm system here, it is applicable to the systems with any number of axes. By using the variable minimum supply pressure together with the maximum valve opening, the energy-efficiency of VPVC is improved compared with a FPVC system. Moreover, due to the feed forward part in VPVC, the dynamic response is much better than a FPVC system with proportional integral position feedback control. The comparison between FPVC and VPVC validated these advantages. The hydraulic power consumption comparison showed that up to 70% saving was achieved by VPVC over FPVC experimentally. If the energy loss via relief valve in FPVC is taken into account, the saving can be increased greatly. In all the comparison tests, the dynamic errors in VPVC were smaller than in FPVC (both were with constant proportional-integral controllers setting). The experimental dynamic errors of VPVC were within 6.5% of the total motion range, compared to 14% for FPVC. And the average dynamic errors of VPVC were within 1.5% of the total motion range. The experiment also showed that the VPVC brought a very quiet operating due to the minimum flow throttling and variable motor speed, which is another significant benefit of VPVC over FPVC.

1. Introduction

Hydraulic actuation, as one of the oldest forms of power transmission, has been playing a very important role in diverse applications due to its high power density, easy to implement linear motion, stepless speed control and good durability despite the rapid development of electric power transmission (Chapple, 2003). The energy efficiency is becoming an important consideration to many hydraulic applications (Murrenhoff, Sgro & Vukovic, 2014). As a fast growing customer to hydraulic actuation, hydraulic mobile robots require energy-efficiency and low-cost as well as good control precision (Guizzo & Deyle, 2012). For a multi-load branch system with one single power source, such as a mobile robot, the fixed supply pressure valve-controlled (FPVC) hydraulic system is a common and simple control algorithm. But energy has to be dissipated across the relief valve and control valves in a FPVC system (Habibi & Goldenberg, 1994). Lots of optimizations have been investigated to increase the energy-efficiency. The approaches can be generally classified as focusing the improvement on the valve-controlled method and the implementation on the pump-controlled method (Quan, Quan & Zhang, 2014). Separate meter in and meter out could reduce energy consumption over the control valve by decoupling its two metering orifices (Jansson &

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Palmberg, 1990), and research about the control characteristics and energy saving for motion control and pressure control was presented for different operating conditions (Liu, Yang, Xu & Zeng, 2009). Switching mode control aims to use the on-off ratio instead of the conventional throttling flow control. In order to simulate a switched inertance device more accurately and to get better performance, an analytical method which can describe this switched inertance device in the time domain and frequency domain had been developed successfully (Pan et al., 2014). For the purpose of good switching performance, some improvements for the switching valve like short switching time, low leakage and high flow had been achieved (Van de Ven & Katz, 2010; Hu, Wu, Yuan & Jing, 2011). Varying effective area cylinder is designed to be able to adjust its effective area in real time, which makes all the cylinders in this system have the same load pressure. In the meantime, the power source is controlled to meet this load pressure and the flow rate requirements (Yang, Plummer, Johnston & Xue, 2014). Electro-hydrostatic actuation (EHA) does not require the usage of control valve. It adopts an electric motor connected to a pump, to control the flow rate and pressure of the working fluid to the cylinder by regulating the velocity and torque of the motor. EHA applied on a flight simulator performed a great power consumption saving compared with the traditional FPVC system (for example from 45 kW to 5 kW during one representative motion waveform) (Cleasby & Plummer, 2008). Robotics is another customer of EHA. A commercial EHA system called the Mini Motion Package (MMP) was adopted in a 5 DOF power assistant robot (Khoa, Kim & Ahn, 2012). Has, Rahmat, Husain and Ghazali proposed a Sliding Mode Control (SMC) scheme to compensate the uncertainties and external disturbance in an EHA system, and the simulated results validated this SMC was able to provide a significant energy-efficiency (Has, Rahmat, Husain & Ghazali, 2013). Minav, Pyrhönen and Laurila have validated the energy-efficiency improvement by using a permanent magnet synchronous motor servo drive-based direct pump control method to control the position of an electro-hydraulic forklift without the conventional control valves (Minav, Pyrhönen & Laurila, 2012). Ferreira, Fong and Almeida completed a comparative eco-analysis of a conventional constant-speed pump with throttle valve system and a variable-speed pump system. The analysis considered the energy-efficiency, material cost, life cycle cost and environmental impact. And the results showed that the electronic variable-speed pump system brought large energy and environmental savings in variable-load applications (Ferreira, Fong & de Almeida, 2011). Energy regeneration is also an attractive research field. Yang, Sun and Xu used an accumulator as the energy restoring component in a hydraulic elevator, and the experimental results indicated the saving by this novel design was more than 70.8% compared with a normal valve-controlled hydraulic elevator (Yang, Sun & Xu, 2007). Load sensing system implements a constant pressure drop over the control valve by usage of the pressure compensator, in order to achieve a low pressure loss across the control valves. Djurovic & Helduser proposed a comprehensive design and analysis of electro-hydraulic load sensing (EH-LS) system. The results showed the EH-LS achieved a reduction of the pressure excess of 10–12 bar compared with the traditional hydro-mechanical load sensing system (Djurovic & Helduser, 2004). Mettälä validated the practical energy saving and dynamic response of electro-hydraulic flow matching (EFM) method on a tractor which was driven by a variable displacement pump. A possible further improvement was mentioned that maximizing the valve opening of the highest load branch would bring a 9% improvement on the hydraulic power efficiency (Mettälä, 2007). Cheng adopted the load pressure as a feedback signal and adaptive valve opening regulation in the simulation research on a mini evacuator. The results showed this improved flow matching system had reduced the energy consumption compared with the original open-loop EFM system: the system pressure had been reduced up to 2.8 MPa and the system efficiency could be improved up to 23.3% (Cheng, Xu & Yang, 2014). Using a variable-speed fixed-capacity pump is an alternative way to implement EFM other than a variable displacement pump. Some early applications of speed control pumps have been studied to validate the efficiency improvement (Helduser, 2003). Lovrec, Kastrevc and Ulaga investigated the performance of a speed-controlled constant-displacement pump applied on a load sensing system. The experimental results showed that the speed-controlled pump was more robust, easier to maintenance, cheaper, lower noise and higher efficiency over the whole range (Lovrec, Kastrevc & Ulaga, 2009).

In this paper, a load prediction-based variable supply pressure valve-controlled (VPVC) hydraulic actuation will be studied. VPVC adopts a fixed capacity pump with a servo motor. It is designed to generate a variable and minimum required supply pressure together with the corresponding maximum spool positions to the control valves according to the effective load-prediction for a given motion demand. The performance of the VPVC system and traditional FPVC system will be analyzed and compared by the tests on a two-axis robotic arm system.

The prototype robotic arm used in this project is an inverted robotic leg HyQ-LegV2.1 from Italian Institute of Technology (Fig. 1). The typical hydraulic circuit of such a two-actuator plant is shown in Fig.2.

2. VPVC control algorithm

From the brief introduction above, it is clear that the VPVC controller is required to send out the motor speed command and the control valve commands. The VPVC controller consists of two parts: feed forward part and feedback part. For a multi-axis system which has n actuators, given by a required motion demand $(y_{d\_1} \cdots y_{d\_n})$, the feed forward part is an inverse model which is able to predict the commands: motor speed command ω_m and valve commands $(x_1 \cdots x_n)$. The feedback part is to use the measured positions $(y_1 \cdots y_n)$ and the proportional (integral) controllers to improve the accuracy of the feed forward control. The circumflex (ˆ) represents the output command signal of the feed forward

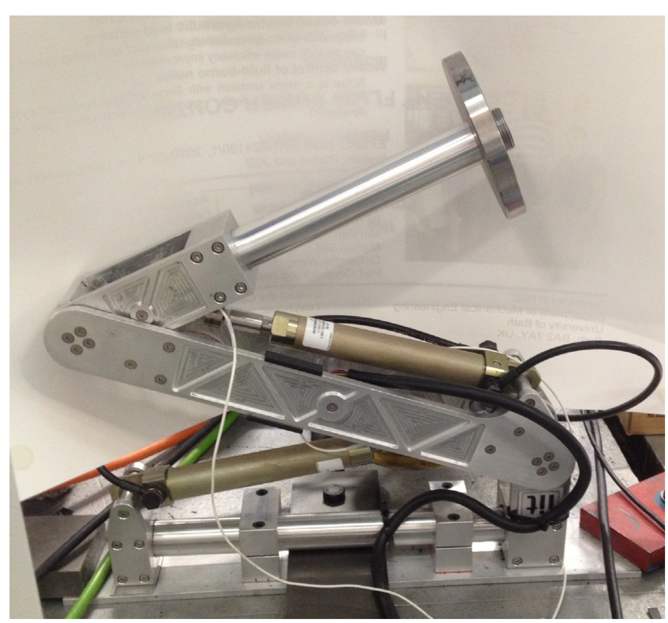

Fig. 1. Two-axis robotic arm (inverted HyQ-leg V2.1 from IIT).