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CONCURRENT CONTROL OF VELOCITY-FORCE CONTROL AND ENERGY-SAVING CONTROL IN HYDRAULIC VALVE-CONTROLLED CYLINDER SYSTEMS

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ABSTRACT

High servo control response and high energy-efficiency are requested in hydraulic servo systems of current hydraulic machines. This investigation concurrently implements energy-saving control and velocity-force control for simultaneously realizing high velocity-force control response and high energy-efficiency for hydraulic valve-controlled cylinder systems. The velocity-force control of the hydraulic cylinder, including 1st stage of velocity control and 2nd stage of force control, can be applied in hydraulic machines, i.e. injection moulding machines. The energy-saving control implemented here contains load-sensing control, constant supply pressure control and constant supply power control. The concurrent control of energy-saving control and velocity-force control of the hydraulic valve-controlled cylinder system becomes a two-input and two-output control problem. For that, an intelligent control strategies using fuzzy sliding mode control is developed. The experimental comparisons of the four different systems, including velocity-force control with load-sensing control, velocity-force control with constant supply pressure control, velocity-force control with constant supply power control and velocity-force control without energy-saving control, are implemented for the same velocity-force profile. The minimum consumed powers in each system are compared. The feasibility of the concurrent control of energy-saving control and velocity-force control is verified experimentally.

KEY WORDS

Key words, concurrent control, velocity-force control, energy-saving control, fuzzy sliding mode control, hydraulic injection moulding machine

INTRODUCTION

Improving the servo control performance and the energy-saving ability is a significant task for today's hydraulic injection moulding machines (HIMM) in face of the competition with electromechanical injection moulding machines (EIMM) [1]. The velocity control, pressure control and phase switching control of the HIMM have been discussed and published in general terms [1-5]. In the conventional HIMM, the clamping force was controlled indirectly by means of the pressure control of the clamping cylinder via a servo valve. However, direct clamping force control can perform more accurate clamping force response. Specific research on the clamping FC of the HIMM is still rare. Besides, researches on the HIMM are usually concentrated on the improvement of servo control performance, and rarely on the improvement of energy efficiency. However, the enhancement of energy efficiency in HIMM has become very important and a decisive factor in competition with the EIMM [1]. The study about the integrated control of the velocity control (VC) and energy-saving control (ESC) in the HIMM was published firstly in the research of Chiang, et al. [3]. Chiang et al. [6] discussed the parallel control of path control and ESC in hydraulic valve-controlled cylinder systems (HVCCS). As the clamping force control only requires high pressure but few volume flow such that only low power is in demand, and the energy efficiency is very low in the conventional HIMM. With the inherent lower efficiency, it is expected that the integrated control system can make a substantial improvement. In this paper, a novel solution is implemented for the integrated control of the velocity-force control and the energy-saving control for simultaneously realizing accurate velocity-force control response and high energy efficiency in the HIMM.

Today's HIMMs are mostly fitted with HVCCS, therefore the integrated control of velocity-force control and energy-saving control in the HVCCS could prove to be a significant improvement of the high velocity-force control performance and high energy efficiency for the HIMM. The conventional HVCCS with a relief valve and constant displacement pumps for setting the maximum supply pressure, perform good servo control response, but have low energy efficiency. For that reason, the energy-saving control, such as load-sensing control (LSC) and constant supply pressure control (CSPC), is introduced to improve the energy efficiency in the HVCCS. The LSC enables the supply pressure to be adjusted according to the load-sensing pressure of the hydraulic actuator thereby achieving the energy-saving effects by keeping a constant difference between the supply pressure and the load-sensing pressure [3,6,7]. Moreover, the integrated control of velocity-force control and energy-saving control in HVCSS is more complicated than the force control or velocity control alone, therefore it is indispensable to develop an appropriate controller to provide the excellent velocity-force control response as well as high energy efficiency for the HIMM.

TEST RIG LAYOUT

Figure 1 schematically depicts the test rig that can be divided into a HVCCS and an electro-hydraulic variable displacement pump system (EHVDPS). The HVCCS works for realizing velocity-force control of the injection cylinder of HIMM; the EHVDPS realizes the energy-saving control in the HIMM. Therefore, the concurrent control system, composed of the velocity-force system and the energy-saving control system, is a TITO control system. Besides, the DSP-based control hardware can be realized for real industrial applications.

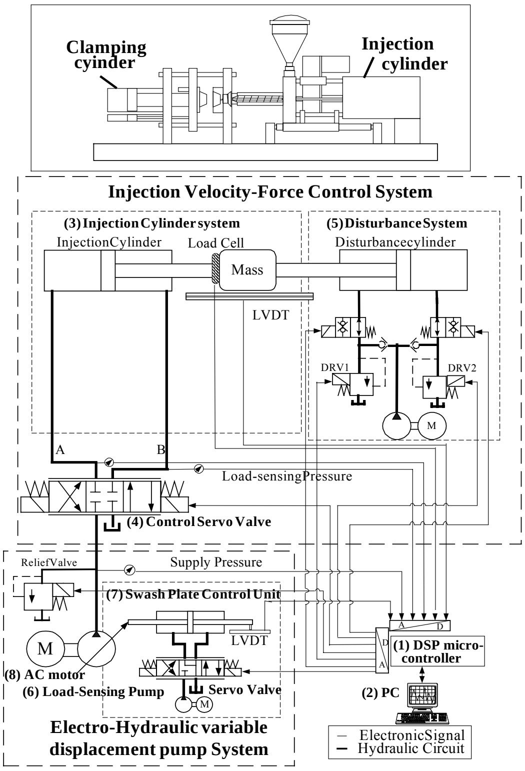


Figure 1 Test rig layout of the integrated control system for injection moulding machines

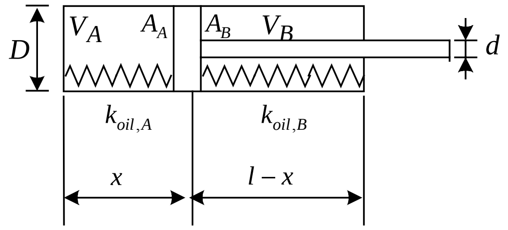


Figure 2 Equivalent springs of disturbance cylinder chambers

Injection velocity-force control system

This system is composed of: (3) an injection cylinder system, (4) a control servo valve and (5) a disturbance system. The injection cylinder system, including a injection cylinder, a load cell and two pressure transducers. The velocity and force signals are measured by the position sensor and load cell, and fed back to the velocity-force controller. The pressure from the load-sensing valve into the hydraulic cylinder, namely the load-sensing pressure p_{LS}, is measured and fed back for energy-saving control.

The disturbance cylinder acts as an equivalent spring for injection force control in this study by means of closing the two solenoid valves. Due to the oil compressibility, the chamber oil of disturbance cylinder can act as hydraulic springs, as shown in Figure 2 [11].

Energy-saving control system

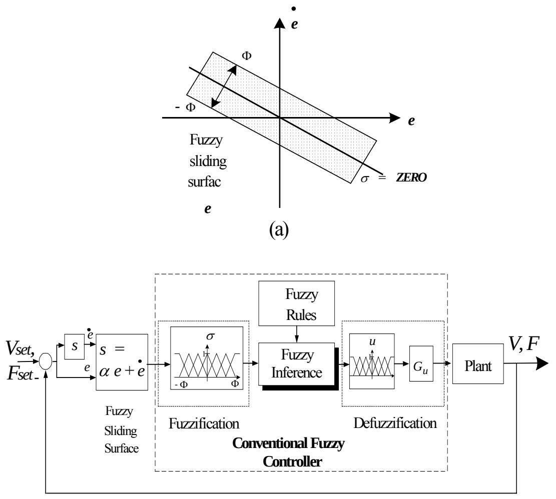
The energy-saving control is implemented by means of the EHVDPS that incorporates: (6) a swash plate piston pump with variable displacement (load-sensing pump), (7) a swash plate control unit, and (8) an AC induced motor. The displacement of the swash plate axial piston pump is adjusted by the angle of the swash plate, which is altered by the swash plate control unit via a small HVCCS with position control of the swash plate.

CONTROLLER DESIGN

In this study, fuzzy sliding mode control is used for decreasing the fuzzy rule numbers. The FSMC is an approach that incorporates the fuzzy control with the sliding-mode control. In many fuzzy control systems, the fuzzy rule base depends on both the control error e and the control error rate $\dot{e}$, which complicates the fuzzy inference rules and the membership functions. For that reason the FSMC introduces a sliding surface function σ to reduce the number of input variables and fuzzy inference rules.

$$\sigma = (\alpha e + \dot{e}) = ZERO \tag{1}$$

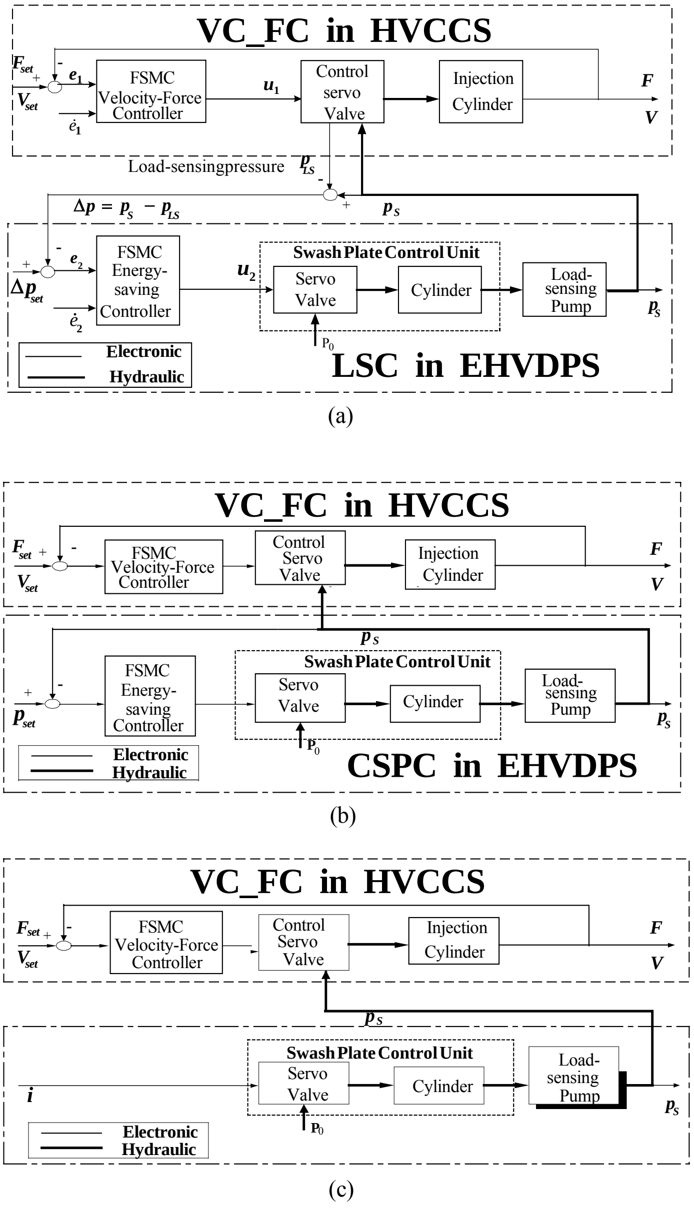
where α is a positive constant that depicts the slope of the fuzzy sliding surface $\sigma = ZERO$, which is a straight line in the phase plane, as shown in Fig. 3(a). Since the robustness is inherent in the sliding-mode control, the stability and robustness of the conventional fuzzy controller can be assured. In addition, it can at the same time improve the chattering phenomena which occurs in the sliding-mode control. In this study, the sliding surface σ and the control input u are both divided into 7 sections by the membership function set. Therefore, instead of 7×7 fuzzy rules with control error e and error rate $\dot{e}$ in the conventional fuzzy control, the FSMC can reduce the fuzzy rules into 7 rules with the fuzzy sliding surface σ. The Mamdani method is used in the fuzzy inference, and the centroid method is used for defuzzification. The block diagram of the FSMC is illustrates in Fig. 3(b). The control block diagrams are shown in Fig. 4.



(a)

(b)

Figure 3 Fuzzy sliding-mode control
(a) fuzzy sliding surface σ
(b) Block diagram of FSMC



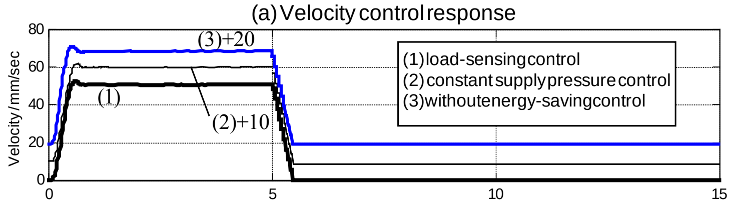
(a)

(b)

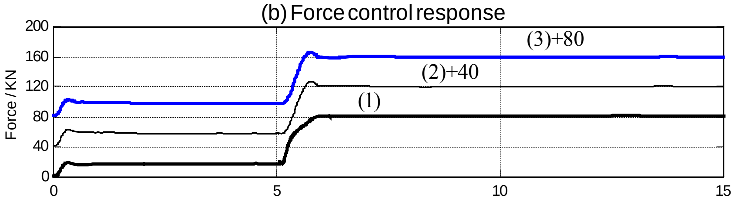
(c)

Figure 4 Block diagrams of the concurrent control systems
(a)(VC_FC + LSC) (b)(VC_FC + CSPC) (c)(VC_FC- ESC)

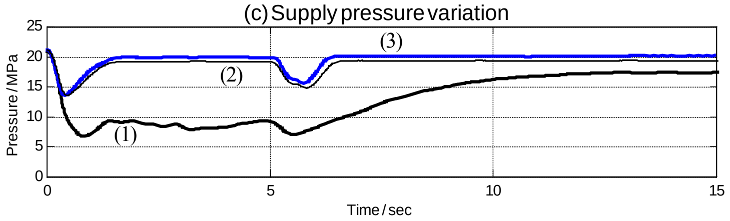
(a) Velocity control response



(b) Force control response



(c) Supply pressure variation



(d) Supply power comparison

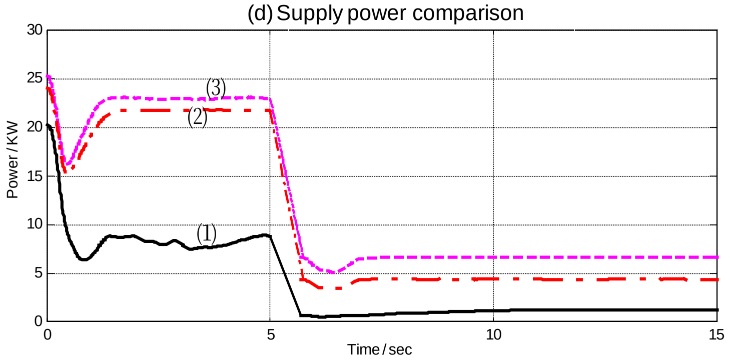


Figure 5 Experimental comparison of three different concurrent control systems: (1) velocity-force control with load-sensing control, Δp_{set}= 2 MPa (0~5sec)、Δp_{set}= 3 MPa (5~15sec) (2) velocity-force control with constant supply pressure control, p_{Sset}= 19 MPa, (3) velocity-force control without energy-saving control, p_{Smax}= 21 MPa

EXPERIMENTAL RESULTS

The injection cylinder performs with constant velocity control firstly for constant feeding of plastic material. Subsequently, force control is performed for moulding injection. Thus, the velocity-force control is requested for the injection cylinder.

The new concurrent control of injection velocity-force control and energy-saving control with FSMC is implemented and verified experimentally. At first, the experiments of the injection velocity-force control are implemented without energy-saving control using FSMC, i.e. (VC_FC-ESC). After that, two different energy-saving control systems, such as load-sensing control (LSC) and constant supply pressure control (CSPC), are integrated with the velocity-force control, i.e. (VC_FC+LSC) and (VC_FC+CSPC).

The nominal experiment conditions are chosen as: the sampling frequency f_s=200Hz, the oil temperature T_{oil}=30~40℃, and the maximum supply pressure p_{Smax}=21MPa.

At last, in order to evaluate the energy-saving effects, the pump energy consumption of the three concurrent control systems, i.e. (1)(VC_FC+LSC), (2)(VC_FC+CSPC) and (3)(VC_FC-ESC) are compared.

Figure 5 indicates the experimental comparison of the concurrent control for the velocity-force control with set velocity V_{set}=50 mm/sec and set force of F_{set}=80 KN under three different energy-saving control systems, namely (1) (VC_FC+LSC), Δp_{set}= 2 MPa (0~5sec)、Δp_{set}= 3 MPa (5~15sec) (2) (VC_FC+CSPC), p_{Sset}= 19 MPa, (3) (VC_FC-ESC), p_{Smax}= 21 MPa. As shown in

Fig. 5(a), velocity control is performed during 0~5sec and can be achieved in all the three systems without obvious control performance difference. Figure 5(b) shows the force control comparison during 5~15sec. The force control performance is almost the same. Figure 5(c) shows the supply pressure variation of the three systems. The supply pressure of (VC_FC+LSC) varies with the load-sensing pressure. The supply pressure of (VC_FC+CSPC) can be controlled to keep constant supply pressure 19 MPa; The supply pressure of (VC_FC-ESC) almost reach the maximum supply pressure p_{Smax}= 21 MPa set by the relief valve. Figure 5(d) clarifies the pump supply power of the three concurrent control system, which can be computed by

$$\mathbf{P}_{EM} = \frac{\mathbf{P}_P}{\eta_{mech}} = \frac{P_S \cdot Q}{\eta_{mech} \cdot \eta_{vol}} = \frac{P_S \cdot Q}{\eta_{total}} = \frac{P_S \cdot n \cdot q_{\max} \cdot x_p}{\eta_{total} \cdot x_{p,\max}} \qquad (2)$$

where

$\mathbf{P}_{EM}$,: power of electrical motor

η_{total} : total efficiency of pump

η_{mech} : mechanical efficiency of pump

η_{vol} : volumetric efficiency of pump

p_S : supply pressure

Q: volume flow of pump

$q_{\max}$: max. displacement of pump

n: rotational speed

$x_{p,\max}$: max. swash plate angle of pump

x_p : swash plate angle of pump

p_s and x_p are directly measurable by the pressure transducer and the position sensor. The constant rotational speed in the EHVDPS is at n=1760 rpm. The total efficiency of the pump can be estimated from the pump performance curve supported by the pump supplier. The (VC_FC+LSC) system consumes the least power. The (VC_FC+CSPC) system performs also with energy-saving ability.

CONCLUSIONS

This paper develops the new strategy for the concurrent control of injection velocity-force control and energy-saving control in a hydraulic injection machine. The experimental results verify the feasibility of the integrated control systems in the HIMM, including (VC_FC+LSC) and (VC_FC+CSPC). for simultaneously achieving excellent velocity-force control performance and high energy efficiency.

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