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Energy saving control in separate meter in and separate meter out control system[☆]

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ABSTRACT

With the demand for energy efficiency in electro-hydraulic servo system (EHSS) increasing, the separate meter in and separate meter out (SMISMO) control system draws massive attention. In this paper, the SMISMO control system was decoupled completely into two subsystems by the proposed indirect adaptive robust dynamic surface control (IARDSC) method. Besides, a fast parameter estimation scheme was proposed to adapt to the parameter change for a better estimation performance. Also, a supply pressure controller with a disturbance observer and a supply flow rate controller with a grey model predictor were investigated and employed to save the power consumption. Finally, experimental results showed that the proposed IARDSC could achieve a good trajectory tracking performance with the fast parameter estimation. Meanwhile, the two energy saving techniques were validated.

1. Introduction

As applications of EHSS become more and more popular, the demand for low cost, high-level control performance and significant energy saving schemes get stronger and stronger. Generally, the control performance can be seen as the fundamental index in this kind of systems and many control algorithms have been issued (Chen et al. 2016b; Guan & Pan, 2008; Yao, Bu, & Chiu, 2001; Yao, Bu, Reedy, & Chiu, 2000). As for energy saving, the hydraulic energy E from t_0 to t_1 can be defined as:

$$E = \int_{t_0}^{t_1} P_s(\tau)Q_s(\tau)d\tau \tag{1}$$

where P_s is the fluid source supply pressure and Q_s is the fluid source supply flow rate. Obviously, two ways can be utilized to reduce the usage of energy:

- Reducing the fluid source supply pressure $P_s(t)$.
- Reducing the fluid source supply flow rate $Q_s(t)$.

On one hand, only taking reducing the fluid source supply pressure into consideration, pressures at the two cylinder chambers are desired to be as low as possible when a certain pressure difference is kept to maintain the motion task. Thus, independent control of two chamber pressures is one way to save energy. On the other hand, only considering reducing the fluid source supply flow rate, the fluid source is required to provide enough flow rate to maintain the given motion trajectory of load. Thus, reducing the supply flow rate appropriately is another way to decrease the power consumption.

For this issue of energy saving, many configurations have been employed in EHSS, such as mobile hydraulic valve, load sensing (Breeden, 1981) and the proposed SMISMO control systems (Jansson & Palmberg, 1990). Eliminating the mechanical linkage between the meter-in and meter-out orifices is a well known technique and has been used in hydraulic industry for several years. For example, Liu and Yao (2006, 2008), Yao and DeBoer (2002) and Yao and Liu, (2002) have done trajectory tracking control utilizing five high speed switch valves, and both good trajectory following precision and energy saving characteristic have been achieved. Liu, Xu, Yang, and Zeng (2009a), Liu, Xu, Yang, and Zeng (2009b) and Liu, Xu, Yang, and Zeng (2009c) have done some comparative simulations between SMISMO valve arrangement control systems and traditional proportional direction control systems, which showed the better energy saving characteristic in SMISMO control systems. Aardema (1996) used two directional control valves and (Chen, Wang, Wang, & Ma, 2016a) used two servo valves to do the same research: One valve controlled the chamber flows of head end and the other controlled the chamber flows of rod end. In addition, the usage of

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four independent valves of either poppet type or one-way unidirectional type is a more common scheme, which makes sure that the meter-in and meter-out flow can be truly independently controlled. This scheme is used in many studies among the mobile hydraulics industry (Aardema & Koehler, 1999; Book & Goering, 1999; Chen et al., 2016a). In order to obtain the hardware capability of independent control of each meter-in and meter-out ports, the 'Independent Metering Valve' (Aardema & Koehler, 1999) or 'Smart Valve' (Book & Goering, 1999) is involved, which makes it available to control both cylinder states completely. When the hardware flexibility is properly utilized, the dual objectives of precise motion trajectory tracking control and high hydraulic energy efficiency can be achieved to some extent.

With the increasing demand for a better control performance, it is necessary to explicitly consider the effect of nonlinearities and uncertainties associated with the electro-hydraulic systems. As such, the design methodology 'integrator backstepping (IB)' has received a great deal of interest. The book by Krstic, Kanellakopoulos, and Kokotovic (1995) developed the backstepping approach to the point of a step by step design procedure. In the recent 20 years, adaptive robust control based on the idea of IB gains vast attention in many literatures, such as adaptive robust control (ARC) (Escareno, Rakotondrabe, & Habineza, 2015; Pazelli, Terra, & Siqueira, 2011; Yao & Tomizuka, 1997) and indirect adaptive robust control (IARC) (Yao & Palmer, 2002). Although an accurate parameter estimation is achieved in ARC&IARC, the estimation method is only applied to constant parameter situations. When the parameters are changing with respect to time, the poor estimation speed makes it difficult to obtain the true values of parameters and then results in poor trajectory tracking performance. Hence, a fast parameter estimation is needed and makes sense here.

Due to the basis of IB technique, the above methods suffer from the problem of 'explosion of terms', that is, the complexity of controller grows drastically as the order of the system increases. Swaroop, Hedrick, Yip, and Gerdes (2000) proposed a dynamic surface control technique to solve this problem by introducing a first-order filter into the synthesized virtual control law at each step of the backstepping design procedure. Literatures show that DSC technique is suitable to solve the 'explosion of terms' problem (Li, Chen, Gan, Fang, & Zhang, 2010; Na, Ren, Herrmann, & Qiao, 2011; Qiu, Liang, & Dai, 2015; Song, Zhang, Zhang, & Lu, 2014). Also, in Song et al. (2014) and Na et al. (2011), DSC was combined with robust and adaptive control to achieve guaranteed performance, respectively. However, when the system suffers from both parameter uncertainty and disturbance, DSC with either adaptation or robustness will fail to achieve a better performance. Therefore, in this paper, both adaptive control and robust control will be combined with DSC, so that the parametric uncertainty and unknown disturbance can be restrained at the same time. By utilizing DSC technique in the IARC design procedure, and with a construction of fast parameter estimation, an IARDSC with fast parameter estimation is proposed to achieve fast and accurate parameter estimation while maintaining a guaranteed performance and eliminating the 'explosion of terms' under parametric uncertainty and unknown disturbance.

The disturbance observer is first proposed in Chen (2003). For systems satisfying the matched conditions, the disturbance observer is a method that has been applied in conjunction with controller (Lu, 2009; Mohammadi, Tavakoli, Marquez, & Hashemzadeh, 2013; Sun, Li, & Lee, 2015). For mismatched nonlinear systems, many significant results with the disturbance observer approach has been investigated in the literature (Yang, Chen, & Li, 2011) recently. For example, Ginoya, Shendge, and Phadke (2014) and Yang, Li, and Yu (2013) proposed a novel sliding mode controller by using disturbance observer to counteract the influence of mismatched uncertainties with a new sliding surface including the estimate of unmatched disturbances. Moreover, it could alleviate the chatter problem in control substantially except for counteracting the influence of mismatched uncertainties. Also, the disturbance observer is utilized in generalized extended state observer based control (Yao, Jiao, & Ma, 2014a, 2014b). Thus, in the SMISMO control system, the disturbance observer can be utilized to estimate the load force, which is taken as a reference to control the fluid source supply pressure for saving energy.

Due to the existence of the pipeline between the pump and valve, there is a delay and drop in the supply flow rate and pressure. Thus, a predictor is needed and a grey model predictor is a suitable choice here. The concept of grey systems is originally developed by Deng (Julong, 1989), and the grey theory is famous for its ability to tackle systems with partially unknown parameters. The technique of grey prediction has been successfully employed to deal with many engineering problems, such as hydraulic system control (Chen, Wang, Ma, & Hao, 2015; Chiang & Tseng, 2004). In grey system theory, a grey prediction model is one of the most important parts, and one core of grey prediction models is GM(1,1) model (Zeng, Liu, & Xie, 2010). Therefore, the GM(1,1) model is employed to predict the motion of load, which can be utilized to control the fluid source supply flow rate for reducing the power consumption.

Based on our published work (Chen et al., 2015), this paper focus on the further research about energy saving control in EHSSs without losing of tracking performance. The main contributions are concluded as follows:

- Our previous proposed study, IARDSC (Chen, Wang, Wang, Zhao, & Shen, 2017) and fast parameter estimation (Hao, Wang, Zhao, & Wang, 2016) were employed to maintain the tracking precision since the SMISMO control system is with internal parameter uncertainties, external disturbances, and the influence of the following energy saving control.
- Two energy saving techniques: reducing the supply pressure by using a disturbance observer and reducing the supply flow rate by using a grey model predictor, were proposed and analyzed.
- To validate the effectiveness of proposed method, comparative experiments were implemented and experimental results showed a significant energy saving performance with the required tracking performance guaranteed.

This paper is organized as follows. The SMISMO control system is modeled in Section 2. In Section 3, the IARDSC and a fast parameter estimation algorithm are proposed for the SMISMO control system. Section 4 gives out the details about two main ways to save energy: reducing the fluid source supply pressure via a load observer to estimate the proper pump pressure and reducing the fluid source supply flow rate by using a grey model to predict the flow rate demand of load. Experimental results are presented in Section 5 to show the effectiveness of the proposed method. Conclusions are drawn in Section 6. Moreover, the related proof is analyzed in the Appendix.

2. System modeling

The SMISMO control system scheme considered here is shown in Fig. 1. This system is mainly composed of a hydraulic cylinder with an inertia load, two proportional directional control valves (PDCV1 & PDCV2), an electro-hydraulic proportional relief valve and the fluid source. The relief valve is intended to control the supply pressure, which is proportional to its control voltage input, while the fluid source, driven by a servo motor, is utilized to control the supply flow rate. Noting that the two PDCVs have different rated flow rates because of the asymmetry of single-rod cylinder. The rated flow rate of the PDCV on the cylinder-end side is larger than that on the rod-end side. Actually, the whole system is a multiple input multiple output (MIMO) system, which can be divided into four single input single output (SISO) subsystems based on their own control input: a motion servo system (control voltage of one PDCV), a backpressure regulating system (control voltage of the other PDCV), a supply pressure control system (control voltage of relief valve), and a supply flow rate control system (control voltage of servo motor). However, every subsystem is not independent of others and couples together, especially the former two subsystems. Therefore, they