ISA Transactions ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Research article

Robust adaptive precision motion control of hydraulic actuators with valve dead-zone compensation☆

Wenxiang Deng, Jianyong Yao*, Dawei Ma

School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China

ARTICLE INFO

Article history:
Received 22 February 2017
Received in revised form
12 June 2017
Accepted 21 July 2017

Keywords:
Dead-zone inverse
Robust control
Adaptive control
Hydraulic actuator
Disturbance suppression

ABSTRACT

This paper addresses the high performance motion control of hydraulic actuators with parametric uncertainties, unmodeled disturbances and unknown valve dead-zone. By constructing a smooth dead-zone inverse, a robust adaptive controller is proposed via backstepping method, in which adaptive law is synthesized to deal with parametric uncertainties and a continuous nonlinear robust control law to suppress unmodeled disturbances. Since the unknown dead-zone parameters can be estimated by adaptive law and then the effect of dead-zone can be compensated effectively via inverse operation, improved tracking performance can be expected. In addition, the disturbance upper bounds can also be updated online by adaptive laws, which increases the controller operability in practice. The Lyapunov based stability analysis shows that excellent asymptotic output tracking with zero steady-state error can be achieved by the developed controller even in the presence of unmodeled disturbance and unknown valve dead-zone. Finally, the proposed control strategy is experimentally tested on a servovalve controlled hydraulic actuation system subjected to an artificial valve dead-zone. Comparative experimental results are obtained to illustrate the effectiveness of the proposed control scheme.

1. Introduction

Hydraulic actuators are ubiquitous in modern industries by virtue of their ability to generate large force/torque output and their high power-to-weight ratios when compared to electrical counterparts. Common applications of hydraulic actuators include vehicle active suspensions [1], hydraulic turbines [2], manipulators [3,4], load simulators [5], aircraft actuators [6], engineering machineries [7,8], and so on. However, high precision motion control of hydraulic actuators has always challenged control theoreticians and engineers due to nonlinear behaviors, parametric uncertainties and unmodeled disturbances which are inherent in hydraulic systems. Though linear control theory based controllers have been extensively employed in many applications, they can only guarantee local stability [9] and become difficult to satisfy the increasing tracking performance demands. Hence, advanced nonlinear control schemes need to be investigated to achieve performance improvement.

To this end, lots of nonlinear controllers have been proposed for motion control of hydraulic actuators during the past several decades. Typically, if the hydraulic system model is exactly known, the nonlinear terms cancellation based feedback linearization control (FLC) [10,11] is the prior choice to obtain asymptotic tracking performance. However, for practical hydraulic systems, it is impossible to acquire all the system model information to have a perfect cancellation. There must exist parameter derivation and unmodeled effects which cannot be expressed by explicit functions. Hence, the FLC controllers designed based on nominal system model may suffer from much degraded tracking performance and even instability. Adaptive controllers [12–14] are extensively used to handle parametric uncertainty but do little about unmodeled disturbance [15]. In order to handle parametric uncertainty and unmodeled disturbance simultaneously, adaptive robust control (ARC) was proposed in [15] and subsequently validated to be effective in many engineering applications [16–18]. Active disturbance rejection adaptive control (ADRAC) strategy which integrates adaptive control and an extended state observer was also investigated in [19,20]. However, only bounded error trajectory tracking performance can be guaranteed by both ARC and ADRAC when existing time-variant disturbance. A robust feedback control scheme called the robust integral of the sign of the error (RISE) was developed in [21] to attenuate smooth enough and bounded modeling uncertainties with asymptotic tracking performance, which is significant for engineering practice.

☆This work was supported in part by the National Natural Science Foundation of China (Grant No. 51675279), in part by the Natural Science Foundation of Jiangsu Province (Grant No. BK20170035), in part by the Fundamental Research Funds for the Central Universities (Grant No. 30917011205), and in part by the Young Elite Scientist Sponsorship Program by CAST (Grant No. 2016QNRC001).

* Corresponding author.
E-mail addresses: wxdeng_njust@163.com (W. Deng), jerryyao.buaa@gmail.com (J. Yao), ma-dawei@163.com (D. Ma).

http://dx.doi.org/10.1016/j.isatra.2017.07.022
0019-0578/© 2017 Published by Elsevier Ltd. on behalf of ISA.

To reduce the feedback control efforts and further improve the tracking accuracy, the adaptive version RISE controllers were also investigated, such as in [22–24]. Though the RISE-based controllers can obtain excellent asymptotic tracking with zero tracking error, unfortunately, they can only handle matched disturbance while the practical hydraulic system model contains unmatched disturbance (e.g., nonlinear friction effects). Hence, the asymptotic tracking problem of hydraulic actuators with consideration of parametric uncertainties, matched and unmatched disturbances needs to be further investigated.

In addition to the above mentioned various modeling uncertainties, this paper also explicitly considers the unknown valve dead-zone effects which may deteriorate the control performance and even lead to instability. Dead-zone problem is a critical issue in proportional control field of hydraulic controlled systems with proportional valve. It can be said that dead-zone nonlinearity is the major obstacle of improving the tracking accuracy for these proportional systems in a sense, hence suitable dead-zone compensation technique possesses many practical meanings. As pointed out in [26,29], there are generally two kinds of ways in the literature to alleviate the effects of dead-zone. One is inverse function based active dead-zone compensation control, examples like in [3,25–27,34,35]. Specifically, nonlinear adaptive control schemes were developed in [3,25–27] to compensate the dead-zone effects by updating the unknown dead-zone inverse parameters online. With the linearization of the hydraulic system model, linear controllers with active dead-zone compensation mechanisms were also designed in [34,35]. It is worth noting that the dead-zone inverse constructed in [3,25–27,34,35] are discontinuous, which might leads to the control input chattering. Moreover, the linear control methods in [34,35] will cause some deviations from the practical systems and may lead to system instability. Hence, in [28], an adaptive controller was developed for nonlinear systems with uncertain dead-zone by using a smooth dead-zone inverse. However, all above active dead-zone compensation based control algorithms can only guarantee bounded output tracking errors. The other way of minimizing the dead-zone effects is to model the dead-zone as a combination of a linear control input with a constant/ time-varying gain and a disturbance-like term, such as in [29–31,36,37]. In those controller designs, the disturbance-like term was lumped into the unmodeled disturbance and then attenuated by various robust control laws. But the methods in [29–31,36,37] can also only obtain bounded tracking performance. The excellent asymptotic tracking performance was achieved in [29] with a novel continuous nonlinear robust control law for a chain of integrators with the presence of dead-zone nonlinearity and unmodeled disturbance. However, since the characteristics of dead-zone are not explicitly taken into consideration and compensated in all those control designs [29–31,36,37], the output tracking performance especially the steady-state performance might be not good enough [28]. Furthermore, considering that the practical hydraulic system may encounter sever valve dead-zone (i.e., large slopes or breakpoints), the burden of the robust control law will be increased by treating the dead-zone as a disturbance-like term [32]. For such case, high feedback gains have to be employed in the robust control which might excite the unmodeled high-frequency system dynamics and lead to instability.

In this paper, a robust adaptive controller is proposed for high performance motion control of hydraulic actuators subjected to parametric uncertainties, unmodeled disturbances and unknown valve dead-zone by integrating the nonlinear robust control structure in [29] with adaptive control via backstepping. The effects of valve dead-zone are minimized by employing a smooth dead-zone inverse in [28]. The unknown dead-zone parameters and other system parameters are estimated by the synthesized adaptive laws, and the unmodeled disturbances in conjunction with the approximation error caused by the smooth inverse dead-zone are suppressed by continuous nonlinear robust feedback control law. The contributions of this paper consist of the following aspects. 1) The model-based adaptive feedforward compensation technique is combined with the nonlinear robust control structure in [29] to achieve tracking performance improvement. 2) By using the continuously differentiable property of the nonlinear robust control law, it is extended to handle the unmatched disturbance case in hydraulic system. 3) The disturbance upper bounds can be updated online via adaptive laws, which increases the controller operability in practice. 4) To the best of our knowledge, this paper is the first result that asymptotic output tracking performance with zero error can be obtained for hydraulic servo systems with unknown valve dead-zone by using a continuous control input. To verify the effectiveness of the proposed control scheme, comparative experimental results are obtained for a hydraulic actuator preceded by a simulated valve dead-zone.

This paper is arranged as follows. Problem formulation and dynamic models are shown in Section 2. Section 3 presents the design procedure of the proposed robust adaptive controller and its main theoretical results. Experimental results are obtained in Section 4. Some conclusions are made in Section 5.

2. Problem formulation and dynamic models

The hydraulic actuation system considered in this paper is depicted in Fig. 1. As seen, the inertia load is driven by a valve controlled double-rod hydraulic cylinder. The goal is to make the inertia load to track any smooth motion trajectory as closely as possible with a continuous control input. The force balance equation of the inertia load can be described by

$$m\ddot{x}_p = P_L A_p - B\dot{x}_p - A_f S_f(\dot{x}_p) + f(t) \tag{1}$$

where m and x_p represent the mass and the displacement of the load, respectively; P_1 and P_2 are the pressures inside the two chambers of the cylinder, and $P_L = P_1 - P_2$ is the load pressure; A_p is the efficient ram area of the cylinder; B is the combined coefficient of the modeled damping and viscous friction on the load and the cylinder rod; $A_f S_f$ represents the approximated Coulomb friction, in which A_f is the Coulomb friction amplitude and S_f is a smooth function to approximate the discontinuous sign function; and $f(t)$ is the lumped disturbance includes unmodeled nonlinear friction, unconsidered dynamics, etc.

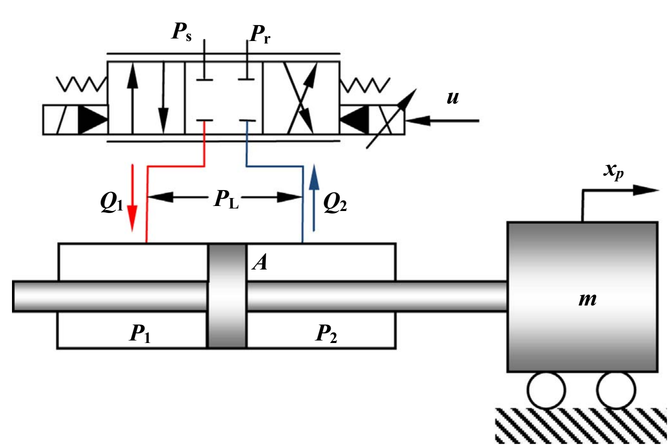

Fig. 1. Schematic diagram of the double-rod electrohydraulic servo system.