Mechatronics 40 (2016) 78–86

Contents lists available at ScienceDirect

Mechatronics

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

Adaptive integral robust control of hydraulic systems with asymptotic tracking[☆]

Guichao Yang, Jianyong Yao[*], Guigao Le, Dawei Ma

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

ARTICLE INFO

Article history:
Received 2 February 2016
Revised 29 September 2016
Accepted 1 October 2016

Keywords:
Adaptive control
Integral robust control
Hydraulic system
Motion control
Asymptotic tracking

ABSTRACT

In this paper, an adaptive integral robust controller is developed for high accuracy motion tracking control of a double-rod hydraulic actuator. We take unknown constant parameters including the load and hydraulic parameters, and lumped unmodeled disturbances in inertia load dynamics and pressure dynamics into consideration. A discontinuous projection-based adaptive control law is constructed to handle parametric uncertainties, and an integral of the sign of the extended error based robust feedback term to attenuate unmodeled disturbances. Moreover, the present controller does not require a priori knowledge on the bounds of the lumped disturbances and the gain of the designed robust control law can be tuned itself. The major feature of the proposed full state controller is that it can theoretically guarantee global asymptotic tracking performance with a continuous control input, in the presence of various parametric uncertainties and unmodeled disturbances such as unmodeled dynamics as well as external disturbances via Lyapunov analysis. Comparative experimental results are obtained for motion control of a double-rod hydraulic actuator and verify the high-performance nature of the proposed control strategy.

1. Introduction

Many hydraulic actuation applications have been put into use in industry on account of the advantages of small size-to-power ratios, high response, high stiffness and large force/torques output; examples like vehicle active suspensions [1–4], hydraulic machines [5–7], robots and manipulators [8–12], anti-lock braking systems [13–15], hydraulic load simulators [16–19], and so on. However, hydraulic systems are highly nonlinear systems with many uncertainties due to the nonlinear dynamics of cylinder and uncertain fluid parameters. Such characteristics bring some difficulties to develop high-performance closed-loop controllers.

To meet the increasingly rigid performance demands in high performance tracking, in recent years, several techniques especially nonlinear control schemes which can achieve a better performance than conventional linear controllers have been developed for the hydraulic system, such as adaptive control [20–22] (AC), robust control [23–25], disturbance observer based control [26–28], and so on. For nonlinear adaptive control and robust control, they improve the control performance of hydraulic systems from different aspects and they have their own advantages and disadvantages. To integrate the fundamentally different working mechanisms of adaptive control and robust design, Yao and Tomizuka [29] have proposed the adaptive robust control (ARC) approach which effectively combines the design techniques of adaptive control and deterministic robust control (DRC) to lay a solid foundation for the design of new intelligent controllers. The proposed ARC achieves a guaranteed performance as DRC in terms of both transient error and final tracking accuracy in general. And this result overcomes the drawbacks of poor transient performance and poor robustness to uncertain nonlinearities of AC. The ARC approach is conceptually simple and amenable to implementation, and has been successfully applied in many industrial applications [2,3,11,12,16-18,30–33]. However, it is worth to note that the ARC scheme relies on precise modelling of the considered system, and potential large unmodeled disturbances may severely exacerbate the tracking performance [26]. To compensate possible large disturbances existing in hydraulic systems in ARC design, a novel linear extended state observer based ARC method has been proposed in [26]. In addition, theoretical and experimental results have verified the excellent tracking performance of the proposed approach in [26]. Nevertheless, aforementioned nonlinear design procedures can only ensure the convergence of the tracking error to a residual bounded set with size of the order of the disturbance magnitude when facing various uncertainities. Such property may be unacceptable in practice, especially in the situations which have high accuracy requirements. And an asymptotic output tracking performance is particularly significant for the high accuracy control of hydraulic systems since uncertainties are the main obstacles for high-precision tracking, especially at low velocity region [34].

[☆] This paper was recommended for publication by Associate Editor M. Moallem

[*] Corresponding author.
E-mail address: jerryyao.buaa@gmail.com (J. Yao).

http://dx.doi.org/10.1016/j.mechatronics.2016.10.007
0957-4158/

To achieve the exact tracking performance for hydraulic systems with modeling uncertainties, much work have been done. An adaptive sliding control method has been proposed for an electro-hydraulic system with nonlinear unknown parameters and an asymptotic tracking result has been obtained in [35]. However, the present approach needs the upper bound of the disturbances to be known, which makes it conservative. In [36], the authors researched the real-time position control of an electro-hydraulic system utilizing an indirect adaptive backstepping technique. Also, this control scheme can ensure the whole closed-loop system globally asymptotically stable. Nevertheless, the modeling errors including the external leakage in the hydraulic pressure dynamics are neglected in [36]. Recently, an adaptive controller and a robust integral of the sign of the error controller are integrated via backstepping method for the trajectory tracking control of a hydraulic rotary actuator with structured and unstructured uncertainties in [34]. Although the proposed controller in [34] can theoretically guarantee asymptotic tracking performance in the presence of modeling uncertainties, the load parameters such as mass, damping coefficient and so on have to be assumed known. In addition, the matched modeling errors with respect to control input are not considered and the uppers of the unmatched disturbances need to be known. Moreover, the designed controller contains discontinuous function, which can cause chattering phenomena and may damage the experimental instruments, so the performance of the control system is affected. To deal with the above mentioned problems in [34], an adaptive compensation with a robust integral of the sign of the error feedback is developed for high precise tracking control of hydraulic motion systems, and an asymptotic tracking performance is obtained in the presence of both parametric uncertainties and unmodeled disturbances in [37]. However, it is assumed that the lumped disturbances are smooth enough until the second order time derivative, and the upper bounds of the first and second order time derivatives of the disturbances need to be known. In realistic hydraulic control systems, it is not easy to obtain these upper bounds.

In this paper, by fully considering parametric uncertainties and uncertain nonlinearities, an adaptive integral robust control (AIRC) algorithm will be synthesized for the motion control of a double-rod hydraulic actuator. The improved discontinuous projection method as done in [30] will be used to estimate unknown constant parameters including both the load and hydraulic parameters, and guarantee that the estimate of unknown constant parameters stays in a known bounded region all the time, even when disturbed by unmodeled disturbances [29]. A robust control law based on the integral of the sign of the extended error will be utilized to handle lumped unmodeled disturbances. The main contributions of this paper are given as follows: (i) The proposed control scheme takes not only unmatched disturbances in inertia load dynamics and matched parametric uncertainties in pressure dynamics but also unmatched parametric uncertainties in inertia load dynamics and matched disturbances in pressure dynamics into consideration. (ii) The proposed control approach does not require a priori knowledge on the bounds of the matched and unmatched disturbances, instead, the gain of the designed robust control law can be tuned itself. Not only the developed control scheme which utilizes the full-state information can ensure the control input continuous, but also global asymptotic tracking performance of hydraulic systems existing various uncertainties including structured and unstructured uncertainties is guaranteed. To verify the high performance of the present controller, extensive comparative experimental results are obtained for a double-rod hydraulic actuator.

This paper is organized as follows. Nonlinear model of the considered double-rod hydraulic system is built in Section 2. Section 3 presents the formulation of the design model and the adaptive integral robust controller design procedure and its theoretical results. Experimental results are given in Section 4. Conclusions can be found in Section 5.

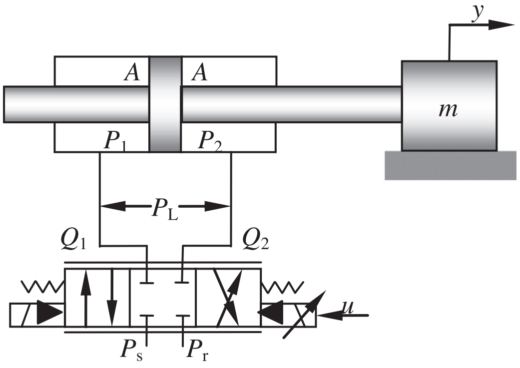

Fig. 1. The architecture of the considered hydraulic system.

2. Nonlinear model of hydraulic system

The system under consideration is the same as that in [31] and [35]. The schematic of the double-rod cylinder hydraulic control system is shown in Fig. 1. The goal is to have the inertia load to track any smooth motion trajectory as closely as possible with a continuous control input. The dynamics of the inertia load can be described by

$$m\ddot{y} = P_L A - \chi^T \phi(\dot{y}) - f(t, y, \dot{y}) \tag{1}$$

where m and y represent the mass and the angular displacement of the load, respectively; $P_L = P_1 – P_2$ is the load pressure in the hydraulic actuator; A is the volumetric displacement of motor; $\chi^T \phi$ represents the modeled nonlinear frictions, in which the amplitude vector χ, denoting different friction levels, may be unknown, but the continuously differentiable shape function vector ϕ is known to capture various nonlinear friction effects, some friction models satisfying above assumptions can be found in [38,39]; and $f(t)$ represents the unmodeled frictions as well as external disturbances.

The pressure dynamics can be written as [26,40]

$$\frac{V_t}{4\beta_e}\dot{P}_L = -A\dot{y} - C_t P_L - q(t) + Q_L \tag{2}$$

where V_t is the total control volume of the actuator; β_e is the effective oil bulk modulus; C_t is the coefficient of the total internal leakage of the actuator due to pressure; $q(t)$ is the modeling error; Q_L is the load flow. The dynamics of servo valve have been considered by some researchers [30,31], but this requires an additional sensor to measure the spool position and only minimal performance improvement can be achieved for motion tracking, so many related works neglect servo valve dynamics, such as in [26,34,35,37]. Since a high-response servo valve is used here, we assume that the control applied to the servo valve is directly proportional to the spool position, hence Q_L can be modeled by [40]

$$Q_L = k_t u \sqrt{P_s - \sigma(u) P_L} \tag{3}$$

where k_t is the total flow gain with respect to the control input u; P_s is the supply pressure of the fluid with respect to the return pressure P_r; and $\sigma(\bullet)$ is defined as follows

$$\sigma(\cdot) = \begin{cases} 1, \text{if} \cdot \geq 0 \\ -1, \text{if} \cdot < 0 \end{cases} \tag{4}$$