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Backstepping Control of Electro-Hydraulic Arm

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***Abstract*—In this study, positioning control of the electro hydraulic systems is considered. Backstepping control strategy is designed by defining an auxiliary error signal. The performance of the controller is investigated by conducting numerical simulations. From the simulation results, it is seen that the control objective achieved successfully. The performance is compared with PI controller via a comparison criteria and it is seen that the backstepping controller has better results in both error and controller performance aspects.**

***Index Terms*—Electro hydraulic systems, backstepping control, position control.**

I. Introduction

Electro hydraulic systems have small size-to-force ratio and ability to apply large force and torque [1]. By virtue to these characteristics electro hydraulic systems are used in loading, positioning and shock absorbing applications in different kind of industries from aerospace to construction [2]. However, these systems have highly nonlinear dynamic models [1]. These nonlinearity makes a challenging problem to construct effective control systems. Even the nonlinear control techniques can not be achieve satisfactory performance since the nonlinearity of the system necessitates fine tuned controller gains.

The studies on electro hydraulic systems generally focused on position controlling and energy saving. Guo *et al.* presented a coupled-disturbance-observer-based position tracking control for a cascade electro-hydraulic system [3]. Yao and Bu used a physical model based adaptive robust controller for the coordinated motion control of a n degree-of-freedom hydraulic arm driven by single-rod hydraulic actuators [4]. In [5], controller was designed to get an excavator to follow typical working motions of a skillful operator such as leveling and truck loading. Tan *et al.* used sliding mode based controller to track desired position for an electro-hydraulic single-rod actuator of a projectile transfer arm. In this study, sliding mode control is utilized to compensate the nonlinearity and parameters uncertainty of electro-hydraulic system [6]. Yingjie *Yingjie* presented a coordinate control method for the boom, arm and bucket cylinders on a hydraulic excavator to perform accurate and effective works [7]. In [8], a load-prediction based method was proposed, in which the supply pressure is varied to track the pressure required by any actuator branch, to increase the energy efficiency. Guo *et al.* proposed a parametric adaptive backstepping control method to improve the dynamic behavior of EHS under parametric uncertainties and unknown disturbance [9], [10]. In [11], H-infinite positional feedback controller is developed to improve the robust performance under structural and parametric uncertainty disturbance in a electro-hydraulic servo system. Jianyong *et al.* designed an adaptive nonlinear optimal compensation controller with nonlinear parameter estimation to improve the torque tracking performance of electro-hydraulic load simulator [12]. Yao *et al.* developed a discontinuous projection-based ARC controller for high-performance robust control of electro hydraulic systems driven by single-rod actuators [1]. Kim *et al.* used nonlinear position tracking controller with a disturbance observer to track the desired position for electro hydraulic actuators [2]. Liu and Daley used optimal-tuning PID control scheme for a rotary hydraulic test rig [13].

In this study, the position tracking of a 1-DOF electro hydraulic system was studied by using backstepping control strategy. While designing the controller rule, the dynamic model in [10] is used. Different from the controller in [10], an auxiliary error signal is used in controller design. The performance of the controller is investigated with simulation studies. The performance of the controller is compared with PI controller results which is usually utilized in the literature. From the results, it is seen that the controller works well and gives better results than the PI controller.

II. System Model

The dynamic model of electro hydraulic system is given as below [10];

$$\begin{aligned} m\dot{x}_2 + bx_2 + Kx_1 &= A_p x_3 - F_L \\ \beta_1 \dot{x}_3 &= A_p x_2 - C_{tl} x_3 \\ &\quad + \beta_2(x_3, x_4)x_4 \\ T_{sv}\dot{x}_4 &= -x_4 + K_{sv}u \end{aligned} \tag{1}$$

where $\beta_1 = \frac{V_t}{4\beta_e}$ and $\beta_2 = \frac{C_d w K_{sv}}{\sqrt{\rho}}\sqrt{p_s - sgn(x_4)x_3}$, $x_1 = y$ and $x_2 = \dot{y}$ are output displacement and displacement velocity of the hydraulic cylinder, respectively, $x_3 = p_L = p_a - p_b$ is load pressure, $x_4 = x_v$ is the spool position of servo valve, p_s is the supply pressure of the pump, C_d is the discharge coefficient, w is the area gradient of the servo valve spool, ρ is density of hydraulic oil, C_{tl} is the coefficient of the total

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leakage of the cylinder, β_e is the effective bulk modulus, $A_p = A_a = A_b$ is annulus area of symmetrical cylinder chamber, V_t is the half-volume of cylinder, m is the load mass, F_L is the external load on the EHA, u is control voltage of servo valve, $sgn()$ is the sign function, K_{sv} is the gain of the control voltage u and T_{sv} is the response time constant of the servo valve.

III. Control Design

The tracking error for the positions of the hydraulics are defined as

$$e = x_{1d} - x_1 \tag{2}$$

where the reference trajectory $x_{1d} \in \mathbb{R}$ and its first and second derivatives are bounded. Auxiliary error term that is used to facilitate the subsequent stability analysis is defined as

$$r = \dot{e} + \alpha e. \tag{3}$$

By differentiating (3) and multiplying both side of equation with m, the following equation is obtained,

$$\begin{aligned} m\dot{r} &= m[\ddot{x}_{1d} + \alpha\dot{e}] - m\dot{x}_2 \\ &= W(x_1, x_2) - A_p x_3 \end{aligned} \tag{4}$$

where

$$W(x_1, x_2) = m[\ddot{x}_{1d} + \alpha\dot{e}] + Kx_1 + bx_2 + F_L. \tag{5}$$

The auxiliary term W_d is defined as

$$W_d(x_{1d}, \dot{x}_{1d}) \triangleq W(x_1, x_2)\Bigg|_{\substack{x_1 = x_{1d} \\ x_2 = x_{2d}}}. \tag{6}$$

Eq. (4) can be rewritten as by adding and subtracting the term $A_p\alpha_1$

$$m\dot{r} = X + W_d + A_p z_1 - A_p\alpha_1 \tag{7}$$

where

$$X \triangleq W - W_d. \tag{8}$$

(8) can be bounded as $\|X\| \leq n_1 \|r\| + n_2 \|e\|$, $n_1, n_2 \in \mathbb{R}^+$. The system errors and control variables are defined as follows

$$z_1 \triangleq x_3 - \alpha_1 \tag{9}$$

$$z_2 \triangleq x_4 - \alpha_2 \tag{10}$$

$$\alpha_1 \triangleq \frac{1}{A_p}(W_d + e + K_r r) \tag{11}$$

$$\begin{aligned} \alpha_2 \triangleq\ & \tfrac{1}{\beta_2}[A_p x_2 + C_{tl}x_3 + \tfrac{\beta_1}{A_p}(\dot{W}_d + K_r\ddot{x}_{1d} + \\ & (1 + K_r\alpha)\dot{e} - \tfrac{K_r}{m}(A_p x_3 - F_L - \\ & Kx_1 - bx_2)) - K_1 z_1 + A_p r] \end{aligned} \tag{12}$$

By using (9)-(12), control rule is designed as follows

$$u = k_u\left[\frac{1}{K_{sv}}(x_4 + T_{sv}\dot{\alpha}_2 - K_{z2}z_2 - \beta_2 z_1)\right] \tag{13}$$

where k_u is general control gain.

IV. Stability Analysis

The stability analysis of the obtained closed-loop error system was investigated by using Lyapunov based method. The Lyapunov function candidate is selected as

$$V = \frac{1}{2}mr^2 + \frac{1}{2}e^2 + \frac{1}{2}\beta_1 z_1^2 + T_{sv}z_2^2 \tag{14}$$

The time derivative of the Lyapunov function candidate can be obtained as

$$\dot{V} = rm\dot{r} + e\dot{e} + \beta_1 z_1\dot{z}_1 + T_{sv}z_2\dot{z}_2. \tag{15}$$

By using (4) and time derivatives of (2), (9) and (10), (15) can be rewritten as

$$\begin{aligned} \dot{V} &= r(X - K_r r) - \alpha e^2 - K_1 z_1^2 - K_{z2}z_2^2 \\ &\leq -\gamma\|\zeta\|^2 \end{aligned} \tag{16}$$

where γ is some positive constant and

$$\zeta = [e^T r^T z_1^T z_2^T]^T. \tag{17}$$

The expression in (16) guaranties the global asymptotic convergence of tracking error and the boundedness of all signals.

V. Simulation Results

The performance of the controller in (13) was evaluated by conducting numerical simulations using Matlab Simulink program. During the simulation the system model given in (2) was used with system parameters in Table I. The gains were selected as $K_{z2} = 1.1$, $K_1 = 1$, $\alpha = 150$, $K_r = 115$ and $K_u = 1e-9$ for backstepping controller and $K_p = 1000$, $K_i = 100$ for PI controller. The controller gains for both backstepping and PI controllers were chosen to give the best performances. The initial values of all states were set to 0. The desired trajectory was selected as $x_{1d} = 26.10^{-3}\sin(2\pi t)$ m. The tracking errors for Backstepping and PI controller are given in Figures 1 and 3 while the control efforts are given in Figures 2 and 4, respectively. From Figure 1, it is seen that the control objective is achieved successfully. To compare the performance of controllers, a comparison criteria was defined. The definition of comparison criteria and comparison results are given in Table II. From Table II, it is seen that backstepping has better performance in both error and controller performance aspects.

VI. Conclusions

In this study, the position tracking of a 1-DOF electro hydraulic system by using backstepping control strategy was presented. The controller was designed by defining an auxiliary error signal. The performance of the controller was investigated by conducting simulation studies and compared with PI controller results which is usually utilized in the literature. From the results, it was seen that the controller work well. To compare the performances of backstepping and PI controller, a comparison criteria was defined. From the criteria, it was seen that the backstepping controller has better performance in both error and controller performance aspects.

TABLE I
SYSTEM PARAMETERS

Parameter	Value
C_d	0.62
p_s	60 Bar
V_t	8.74e-5 m^3
K_{sv}	5e-4 m/V
K	10 N/m
C_{tl}	2.5e-6 $m^3/(s.Bar)$
w	0.024 m
A_p	4.91e-4 m^2
β_e	7000 Bar
T_{sv}	10e-3 s
b	50 N.s/m
ρ	10 Kg/m^3
F_L	10.5 N

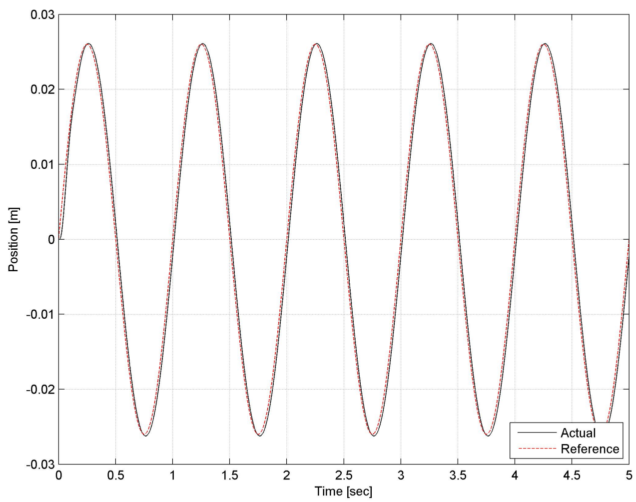

Fig. 1. Tracking performance of backstepping controller.

REFERENCES

[1] B. Yao, F. Bu, J. Reedy, and G. T. C. Chiu, “Adaptive robust motion control of single-rod hydraulic actuators: theory and experiments,” *IEEE/ASME Transactions on Mechatronics*, vol. 5, no. 1, pp. 79–91, Mar 2000.

[2] W. Kim, D. Shin, D. Won, and C. C. Chung, “Disturbance-observer-based position tracking controller in the presence of biased sinusoidal disturbance for electrohydraulic actuators,” *IEEE Transactions on Control Systems Technology*, vol. 21, no. 6, pp. 2290–2298, Nov 2013.

[3] Q. Guo, J.-m. Yin, T. Yu, and D. Jiang, “Coupled-disturbance-observer-based position tracking control for a cascade electro-hydraulic system,” *ISA Transactions*, vol. 68, pp. 367–380, May 2017.

[4] F. Bu and B. Yao, “Nonlinear model based coordinated adaptive robust control of electro-hydraulic robotic arms via overparametrizing method,” in *IEEE Proc. of Inter. Conf. on Robotcs and Automaton*, vol. 1-4, 2001, pp. 3459–3464.

TABLE II
ERROR CRITERIA

	$\int \lvert e \rvert$	$\int \lvert u \rvert$
Backstepping	0.006831	7.677
PID	0.007669	7.778

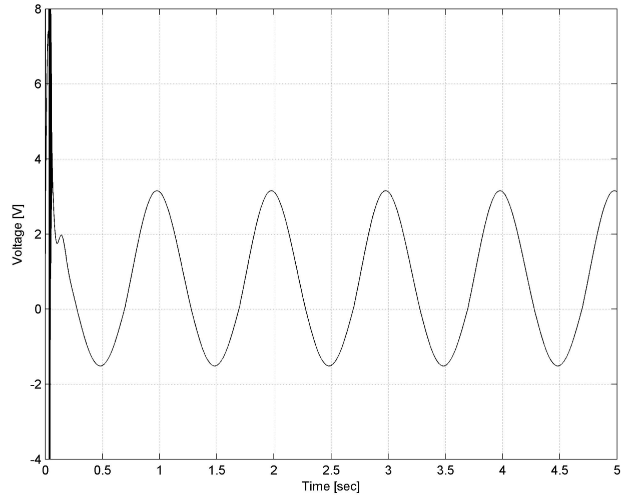

Fig. 2. Control effort of backstepping controller.

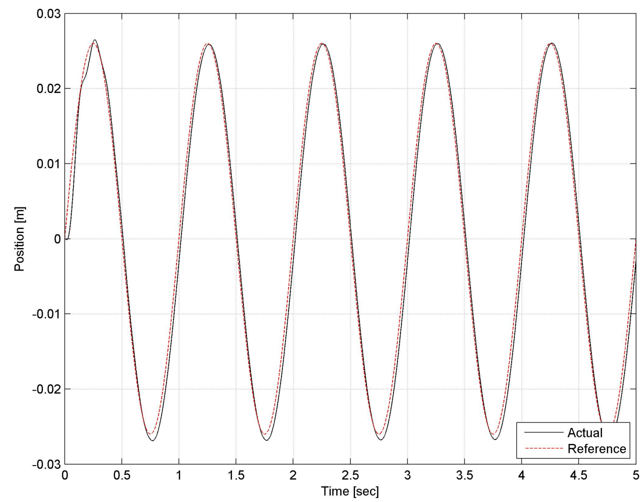

Fig. 3. Tracking performance of PI.

[5] S. Kang, J. Park, S. Kim, B. Lee, Y. Kim, P. Kim, and H. J. Kim, “Path Tracking for a Hydraulic Excavator Utilizing Proportional-Derivative and Linear Quadratic Control,” in *2014 IEEE Conf. on control Applications*, ser. IEEE International Conference on Control Applications, 2014, pp. 808–813.

[6] L. Tian, L. Qian, L. Chen, and W. Zhang, “Sliding Mode Control Based on Backstepping Method for Electro-Hydraulic Single-rod Actuator,” in *IEEE Inter. Conf. on Information and Automation*, 2015, pp. 2326–2329.

[7] G. Yingjie, J. Yanchao, and Z. Qin, “Motion Planning Based Coordinated Control for Hydraulic Excavators,” *Chinese Journal of Mechanical Engineering*, vol. 22, no. 1, pp. 97–101, Feb 2009.

[8] C. Du, A. R. Plummer, and D. N. Johnston, “Performance analysis of a new energy-efficient variable supply pressure electro-hydraulic motion control method,” *Control Engineering Practice*, vol. 60, pp. 87–98, Mar 2017.

[9] Q. Guo, P. Sun, J.-m. Yin, T. Yu, and D. Jiang, “Parametric adaptive estimation and backstepping control of electro-hydraulic actuator with decayed memory filter,” *ISA Transactions*, vol. 62, no. SI, pp. 202–214, May 2016.

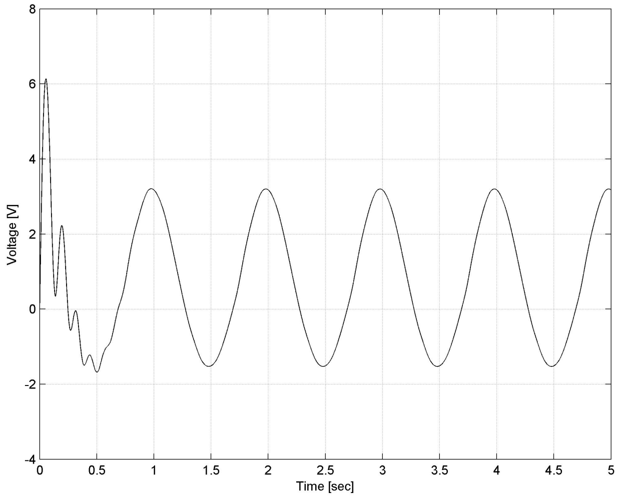

Fig. 4. Control effort of PI.

[10] Q. Guo, Q. Wang, Z. Zuo, Y. Zhang, D. Jiang, and Y. Shi, "Parametric adaptive control of electro-hydraulic system driving two-dof robotic arm," in *2017 IEEE 56th Annual Conference on Decision and Control (CDC)*, Dec 2017, pp. 3283–3288.

[11] Q. Guo, T. Yu, and D. Jiang, "Robust H-infinity positional control of 2-DOF robotic arm driven by electro-hydraulic servo system," *ISA Transactions*, vol. 59, pp. 55–64, Nov 2015.

[12] Y. Jianyong, J. Zongxia, S. Yaoxing, and H. Cheng, "Adaptive nonlinear optimal compensation control for electro-hydraulic load simulator," *Chinese Journal of Aeronautics*, vol. 23, no. 6, pp. 720 – 733, 2010.

[13] G. Liu and S. Daley, "Optimal-tuning pid controller design in the frequency domain with application to a rotary hydraulic system," *Control Engineering Practice*, vol. 7, no. 7, pp. 821 – 830, 1999.