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Lyapunov Based Observer Design for Electro-Hydraulic Arm System

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ABSTRACT

In this paper, a Lyapunov based observer design is proposed to observe the load pressure of electro-hydraulic arm systems. The stability of the observer is investigated by using the Lyapunov based method. In the stability analysis, it is proven that the observer error converge to the vicinity of origin which can be adjusted to be arbitrarily small. The classical PID controller is used to control the position of the electro-hydraulic arm system and keep the system states bounded. The performance of the designed observer is evaluated by computational simulations which are conducted in MATLAB Simulink program. The performance of the observer is tested in two cases: i) noise free case and ii) noise case. In the noisy case, the state x_2 is exposed to the 30 dB additive white Gaussian noise. The computational simulation results are given to demonstrate that the proposed observer work efficiently in both noise free and noisy cases.

Keywords: Electro-hydraulic arm system, Lyapunov based observer, Load pressure

Elektro-Hidrolik Kol Sistemi için Lyapunov Tabanlı Gözlemci Tasarımı

ÖZ

Bu çalışmada, elektro-hidrolik kol sistemlerinin yük basıncını gözlemlemek için Lyapunov tabanlı bir gözlemci tasarımı önerilmiştir. Gözlemcinin kararlılığı Lyapunov tabanlı yöntem kullanılarak araştırılmıştır. Kararlılık analizinde, gözlemci hatasının keyfi olarak küçük olacak şekilde ayarlanabilen orijin civarına yakınsadığı kanıtlanmıştır. Klasik PID denetleyicisi, elektro-hidrolik kol sisteminin konumunu kontrol etmek ve sistem durumlarını sınırlı tutmak için kullanılmıştır. Önerilen gözlemcinin performansı, MATLAB Simulink programında yapılan hesaplamalı benzetimlerle değerlendirmiştir. Gözlemcinin performansı iki durumda test edilmiştir: i) gürültüsüz durum ve ii) gürültülü durum. Gürültülü durumlarda, x_2 durumuna 30 dB ek beyaz Gauss gürültüsüne maruz bırakılmıştır. Hesaplamalı benzetim sonuçları, önerilen gözlemcinin hem gürültüsüz hem de gürültülü durumlarda verimli şekilde çalıştığını göstermektedir.

Anahtar Kelimeler: Elektro-hidrolik kol sistemi, Lyapunov tabanlı gözlemci, Yük basıncı

I. INTRODUCTION

Electro-hydraulic arm systems are utilized in a wide area from industrial applications to civil engineering due to their ability of applying high power. Electro-hydraulic systems (EHS) have a strong nonlinear mathematical models and lots of parameters stays uncertain in practice [1]. Also, the position and pressure measurements are affected by high noise which reduces the control effort [2-4]. Even worse, in many practical applications, the velocity and especially, the pressure sensor are not used due to cost reductions. This led to a wide literature on the observer designs for the EHS.

Mohanty et al. designed a nonlinear observer to estimate the velocity and the parameters of an EHS using pressure measurement only [5]. Sofiane et al. used a discrete time observer to estimate the unmeasurable states and the uncertainties for the electro-hydraulic actuator system [6]. Guo et al. designed an output position feedback control based on an extended-state observer to deal with the load disturbance and the nonlinearity of the EHS [7]. In [1], the backstepping control method with a sliding state observer was developed to deal with systems uncertainties. Yao et al. designed an robust backstepping controller fused with an extended state observer (ESO) to handle the nonlinearity of the system [2]. In [8], an observer based controller is designed to estimate the force-rate and the pressure. The backstepping technique is used to control the EHS and the PI observer is designed to observe the force rate and the pressure. Kim et al. designed an observer-based controller for the position tracking of the EHS of which only the position measurement is available [9]. Guo et al. designed an observer based controller. The designed high gain observer (HGO) estimates full states of EHS and the backstepping method is designed to control the EHS. [10]. In [3], the feedback linearization control was developed to improve monitoring performance and a HGO was designed to predict the exact state of the EHS. In [11], the only system input and the position signal were used to estimate states with an ESO. Liu and Yao designed a sliding mode dynamic flow rate observer to estimate the flow rates of a hydraulic cylinder [12]. In [13], a sampled data distortion observer based on the ESO was used to predict unmeasurable states and uncertainties. Garimella and Yao designed an adaptive robust observer to estimate the unknowns and uncertainties of the system [14]. In [15], a twisting algorithm based observer was designed. In [16], The SMC was designed with the PID type sliding surface to control of EHS and the unknowns and uncertainties of the system is predicted with an ESO thanks to an extended model of EHS. In [17], the adaptive backstepping control which is combined a HGO was proposed to deal with unmeasurable states and uncertainties. In [18], Won et al. proposed the backstepping controller which is using high gain extended state observer (HGESO) with only position feedback. Phan et al. were designed the adaptive fault-tolerant controller with input observer to overcome the sensor fault and the mismatched disturbances/uncertainties [19]. Zou was designed a recursive SMC for position tracking and an ESO was estimated the unmeasured states and unknown disturbances of EHS [20].

In this study, a Lyapunov based observer is recommended to observe the load pressure of the EHS. It is aimed that the observer error converges near the origin, which can be set to be arbitrarily small. The observer is designed by utilizing a Lyapunov based stability analysis. In order to show the performance of the observer, the simulation results are presented with different reference tracking and for noisy free and noisy cases. The simulation studies are conducted with MATLAB Simulink. From the simulation results, it appears that the designed observer works with high accuracy.

II. MATERIAL and METHOD

The system model, the design of the observer and the stability analysis are presented in the subsections of section II.

A. SYSTEM MODEL

The fourth-order state space dynamic model of the EHS is given as follows [21,22]:

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = \frac{1}{m}\left(-Kx_1 - bx_2 + A_px_3 - F_L\right)$$

$$\dot{x}_3 = -\frac{4\,\beta_e\,A_p}{V_t}x_2 - \frac{4\beta_eC_{tl}}{V_t}x_3 + \frac{4\beta_eC_dwK_{sv}}{V_t\sqrt{p}}\sqrt{p_s - sgn(x_4)x_3}\,x_4 \qquad (1)$$

$$\dot{x}_4 = \frac{-x_4 + K_{sv}u}{T_{sv}}$$

where $x_1 = y$ is the displacement of the hydraulic cylinder, $x_2 = \dot{y}$ is the displacement velocity of the hydraulic cylinder, $x_3 = p_L = p_a = p_b$ is the load pressure, $x_4 = x_v$ is the spool position of servo valve and u is the control input of servo valve. The list of the parameters are given in Table 1.

The proposed observer design requires the mechanical system model as in (1) and the closed loop control system hold the next assumptions.

Assumption 1. The system states x_1 and x_2 are available.

Assumption 2. The control signal u is bounded and keeps all system states bounded and continuous.

Assumption 3. The third expression in model in (1) can be rewritten as

$$\dot{x}_3 = f(x_2, x_3, x_4) - \frac{4\beta_eC_{tl}}{V_t}x_3 \qquad (2)$$

where $f(x_2, x_3, x_4)$ is a continuous nonlinear function and it can be bounded as $|f(x_2, x_3, x_4| < \lambda$ where $\lambda \in \mathbb{R}^+$.

Remark 1. It should be noted that since all the system states are bounded as mentioned in Assumption 2, boundedness of function $f(x_2, x_3, x_4) \in \mathbb{R}$ in Assumption 3 is a reasonable assumption.

Table 1. Parameter descriptions of the system.

Parameter	Description
m	Load mass
K	Load spring constant
b	Viscous damping coefficient
A_p	Annulus area of cylinder chamber
F_L	External load of hydraulic actuator
β_e	Effective bulk modulus
V_t	Half-volume of cylinder
C_{tl}	Coefficient of the total leakage of the cylinder
C_d	Discharge coefficient
w	Area gradient of the servo valve spool
K_{sv}	Gain of the servo valve
ρ	Density of hydraulic oil
p_s	Supply pressure of the pump
T_{sv}	Response time constant of the servo valve

B. OBSERVER DESIGN

The main goal of this study is to design a continuous observer to estimate the load pressure of hydraulic cylinder denoted as x_3. The load pressure of the hydraulic cylinder observer, denoted by $\hat{x}_3$ will be designed to observe x_3 while ensuring that the observer error $\tilde{x}_3 = x_3 - \hat{x}_3$ converges to the origin circumference, which can be set to be arbitrarily small. The design is constrained by the

constraint on the right side of the expression of $\dot{x}_3$ in (1) being uncertain as in Assumption 3. To overcome this restriction, the design is began by designing the observer and defining the observer error for the state x_2 which is already available. The estimate of x_3 is placed in the dynamic equation of the observer error of x_2. By this structure, a known observer error could be used in the design of $\hat{x}_3$.

$$\tilde{x}_2 \triangleq x_2 - \hat{x}_2 \tag{3}$$

where $\hat{x}_2$ is estimate of x_2.

By taking the time derivative of (3), the following equation is obtained:

$$\dot{\tilde{x}}_2 \triangleq \dot{x}_2 - \dot{\hat{x}}_2 \tag{4}$$

where $\dot{\hat{x}}_2$ is defined as follows,

$$\dot{\hat{x}}_2 \triangleq -\frac{K}{m} x_1 - \frac{b}{m} \hat{x}_2 + \frac{A_p}{m} \hat{x}_3 - \frac{F_L}{m}. \tag{5}$$

where $\hat{x}_3$ is estimate of x_3.

By substituting (1) and (5) in (4), we obtain the following closed loop error system:

$$\dot{\tilde{x}}_2 \triangleq -\frac{b}{m} \tilde{x}_2 + \frac{A_p}{m} \tilde{x}_3 \tag{6}$$

where $\tilde{x}_3$ is the observer error for x_3 and defined as:

$$\tilde{x}_3 \triangleq x_3 - \hat{x}_3. \tag{7}$$

Based on the subsequent stability analysis, the update rule for $\hat{x}_3$ is designed as follows:

$$\dot{\hat{x}}_3 \triangleq \gamma \frac{A_p}{m} \tilde{x}_2 - k_2 \hat{x}_3 \tag{8}$$

where $\gamma \in \mathbb{R}^+$ and $k_2 \in \mathbb{R}^+$ are the observer gains and k_2 is defined as:

$$k_2 \triangleq k_1 + \epsilon \tag{9}$$

where $k_1 \in \mathbb{R}^+$ and $\epsilon \in \mathbb{R}^+$ are constants. $|\varepsilon| < k_1$ and k_1 is defined as:

$$k_1 \triangleq \frac{4\beta_e C_{tl}}{V_t} \tag{10}$$

It should be noted that $0 < \frac{4\beta_e C_{tl}}{V_t}$.

C. STABILITY ANALYSIS

The stability of the observer has been investigated using the Lyapunov-based method. The Lyapunov function candidate is chosen as follows:

$$V = \frac{1}{2}\gamma \tilde{x}_2{}^2 + \frac{1}{2}\tilde{x}_3{}^2. \tag{11}$$

The time derivative of (11) can be given as:

$$\dot{V} = \gamma \tilde{x}_2 \dot{\tilde{x}}_2 + \tilde{x}_3 \dot{\tilde{x}}_3. \tag{12}$$

By substituting (3), (6), (8) and using (10) and the time derivative of (7), (12) can be rewritten as:

$$\dot{V} = -\frac{b}{m}\gamma\tilde{x}_2{}^2 + \tilde{x}_3\left(\frac{A_p}{m}\gamma\tilde{x}_2 + f(x_2,x_3,x_4) - k_1x_3 - \gamma\frac{A_p}{m}\tilde{x}_2 + k_2\hat{x}_3\right). \tag{13}$$

By using (7) and (9), (13) can be rewritten as:

$$\dot{V} = -\frac{b}{m}\gamma\tilde{x}_2{}^2 + \tilde{x}_3(f(x_2,x_3,x_4) - k_2\tilde{x}_3 + \epsilon x_3)$$

$$= -\frac{b}{m}\gamma\tilde{x}_2{}^2 - k_2\tilde{x}_3 + \tilde{x}_3 f(x_2,x_3,x_4) + \tilde{x}_3\epsilon x_3 \tag{14}$$

By taking the absolute value of some items on the right-hand side in (14) and using Assumption 2 and 3, (14) can be upper bounded as:

$$\dot{V} < -\frac{b}{m}\gamma\tilde{x}_2{}^2 - k_2\tilde{x}_3{}^2 + |\tilde{x}_3||f| + |\tilde{x}_3||\epsilon||x_3|$$

$$< -\frac{b}{m}\gamma\tilde{x}_2{}^2 - k_2\tilde{x}_3{}^2 + |\tilde{x}_3|\xi \tag{15}$$

where

$$\xi = \lambda + \epsilon_2 \tag{16}$$

$$\epsilon_2 > |\epsilon||x_3|. \tag{17}$$

By adding and subtracting $\frac{1}{4(k_2-1)}\xi^2$ to the right-hand side of (15), it can be written as:

$$\dot{V} < -\frac{b}{m}\gamma\tilde{x}_2{}^2 - \tilde{x}_3{}^2 - \left(\sqrt{k_2-1}|\tilde{x}_3| - \frac{1}{2\sqrt{k_2-1}}\xi\right)^2 + \frac{1}{4(k_2-1)}\xi^2$$

$$< -\frac{b}{m}\gamma\tilde{x}_2{}^2 - \tilde{x}_3{}^2 + \frac{1}{4(k_2-1)}\xi^2. \tag{18}$$

Finally, $\dot{V}$ can be upper bounded as follows:

$$\dot{V} < -w\|z\|^2 + \psi \tag{19}$$

where

$$w = min\left(\frac{b}{m}\gamma, 1\right) \tag{20}$$

$$k_2 > 1 \tag{21}$$

$$z = [\tilde{x}_2 \ \tilde{x}_3]^T \tag{22}$$

$$\psi = \frac{1}{4(k_2-1)}\xi^2. \tag{23}$$

From (11) and (18), it is seen that $V(z) \in \mathcal{L}_\infty$ and thus $z(t) \in \mathcal{L}_\infty$. In addition, from (22) and the structure of (11) and (18), it can be said that the trajectory of observer error $\tilde{x}_3$, with any initial value, converges to the origin circumference that can be set to be arbitrarily small by tuning the gain k_2. Therefore, the observer error is globally ultimately bounded when the condition in (21) is satisfied.

III. NUMERICAL SIMULATION RESULTS

In order to substantiate the theoretical results, the designed observer has been tested by using Matlab Simulink program. The system parameters utilized during the simulation are given in Table 2.

Table 2. *System parameters*

Parameter	Value	Unit
C_d	0.62	-
p_s	$4*10^6$	Pa
V_t	$3.417*10^{-5}$	m^3
K_{sv}	$5*10^{-5}$	m/V
K	1000	N/m
C_{tl}	$2.5*10^{-11}$	$m^3/(s.Pa)$
w	0.024	m
A_p	2.01	cm^2
β_e	$2*10^8$	Pa
T_{sv}	12	ms
b	2500	N.s/m
ρ	850	K_g/m^3
F_L	57	N
m	4.845	kg

The following PID controller is used to control the position of the EHS and keep the system states bounded,

$$u = K_p e + K_d \dot{e} + K_i \int e \qquad (24)$$

where $e = x_1 - x_{1d}$. The control gains are selected as $K_p = 1000$, $K_d = 10$ and $K_i = 100$.

The performance of the observer is tested for three cases as set point tracking, sinusoidal reference trajectory tracking, and variable set point trajectory cases with and without noise. In the noisy cases, 30 dB additive white Gaussian noise is added to the state x_2. The observer gains are selected as $\gamma = 5 * 10^{14}$ and $k_2 = 5$ for the noisy free cases and the observer gains are selected as $\gamma = 5 * 10^{10}$ and $k_2 = 500$ for the noisy cases.

A. SET POINT TRACKING

The desired trajectory is selected as $x_{1d} = 0.005$ m. The initial values of all states are set to zero. The designed observer performance is tested in two different situations, noisy and noiseless. In both cases, the desired trajectory of the EHS has not been changed. The observer gains are selected as $\gamma = 5 * 10^{14}$ and $k_2 = 5$ for the noisy free cases and the observer gains are selected as $\gamma = 5 * 10^{10}$ and $k_2 = 500$ for the noisy cases. The control signals and the tracking performance of PID controllers are given in Figures 1 and 3 and Figures 4 and 6, respectively for noisy free and noisy cases. The tracking performance of the observer is given in Figures 2 and 5 for the noise free case and the noisy case, respectively. From Figure 2, it is clear that the observer reaches the actual value quickly and successfully in the noise free case. From the Figure 5, it clear that the observer output tracks the shape of the actual signal successfully in the case of the noisy measurements.
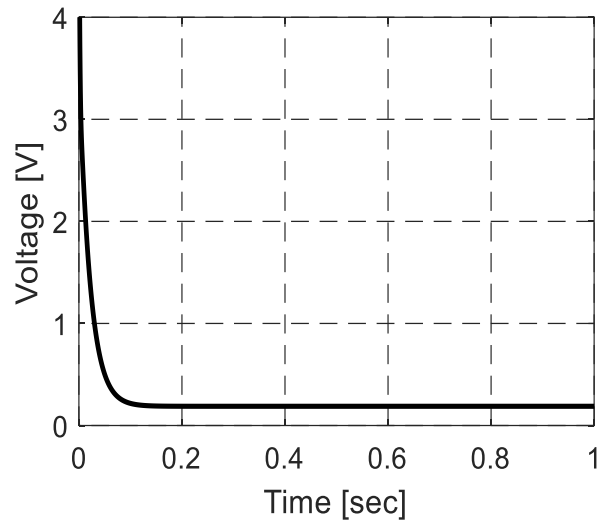
Figure 1. *The control signal of set point tracking for the noise free case.*
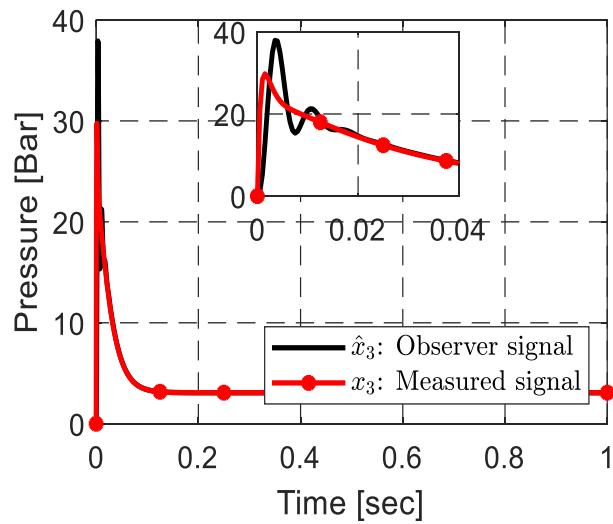

Figure 2. *The set point tracking performance of the observer for the noise free case.*
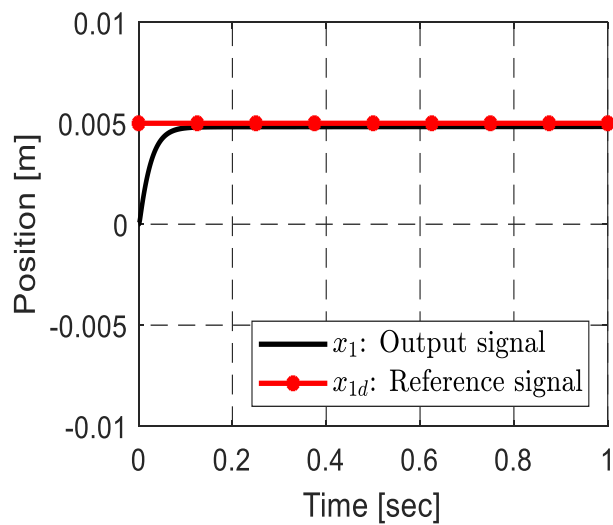

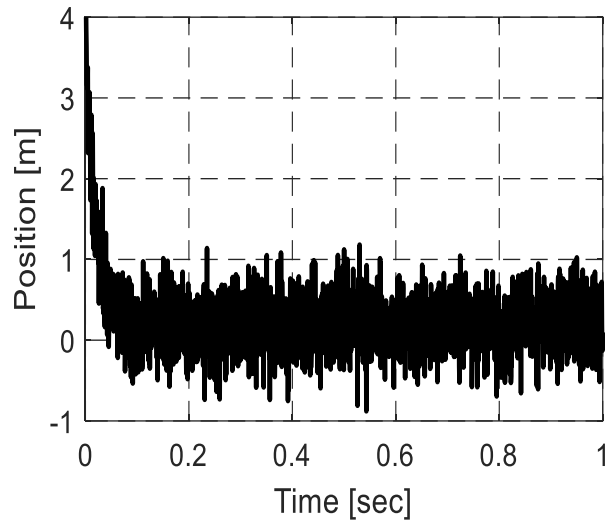**Figure 3.** *The set point tracking performance of the PID controller for the noise free case.*

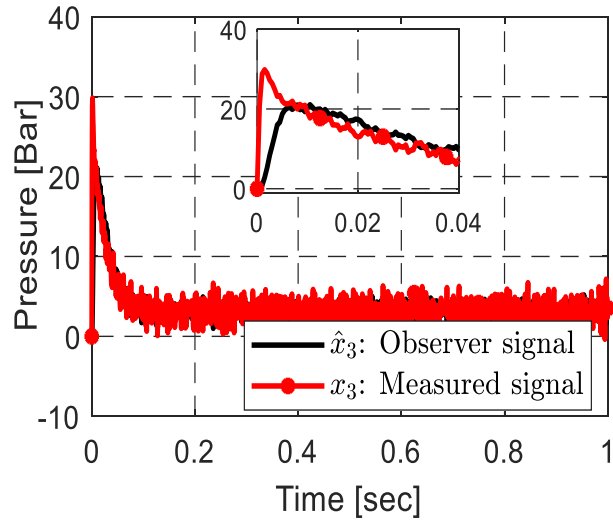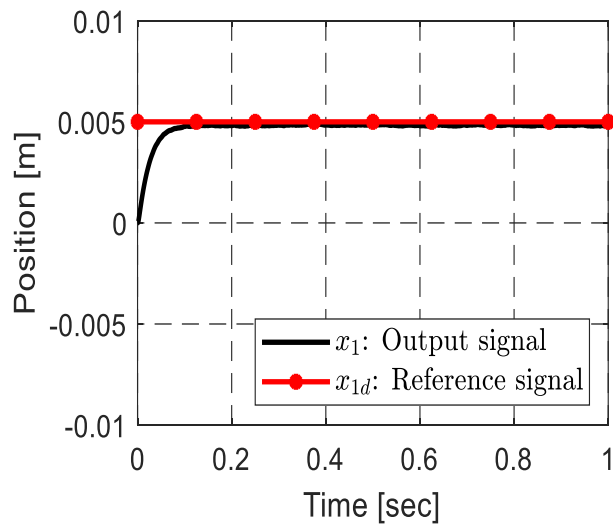**Figure 4.** *The control signal of set point tracking signal for the noisy case.*

Figure 5. *The set point tracking performance of the observer for the noisy case.*

Figure 6. *The set point tracking performance of the PID controller for the noisy case.*

B. SINUSOIDAL REFERENCE TRAJECTORY TRACKING

The desired trajectory is selected as $x_{1d} = 26.10^{-3} \sin(2\pi t)$m. The initial values of all states are set to zero. The designed observer performance is tested in two different situations, noisy and noiseless. In both cases, the desired trajectory of the EHS has not been changed. The observer gains are selected as $\gamma = 5 * 10^{14}$ and $k_2 = 5$ for the noisy free cases and the observer gains are selected as $\gamma = 5 * 10^{10}$ and $k_2 = 500$ for the noisy cases. The control signals and the tracking performance of PID controllers are given in Figures 7 and 9 and Figures 10 and 12, respectively for noisy free and noisy cases. The tracking performance of the observer is given in Figures 7 and 11 for the noise free case and the noisy case, respectively. From Figure 2, it is clear that the observer reaches the actual value quickly and successfully in the noise free case. From the Figure 11, it clear that the observer output tracks the shape of the actual signal successfully in the case of the noisy measurements.
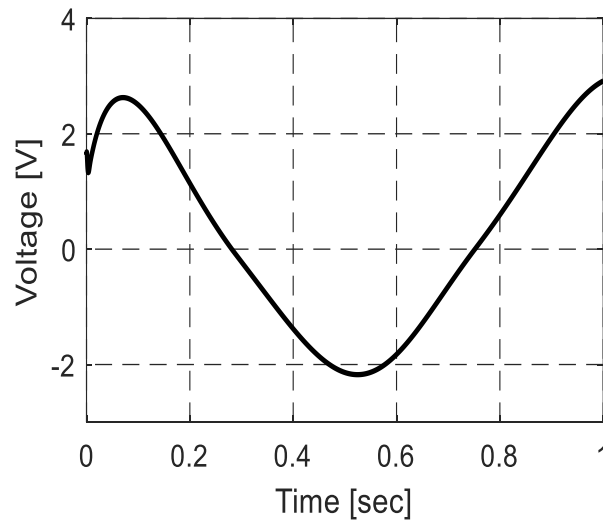

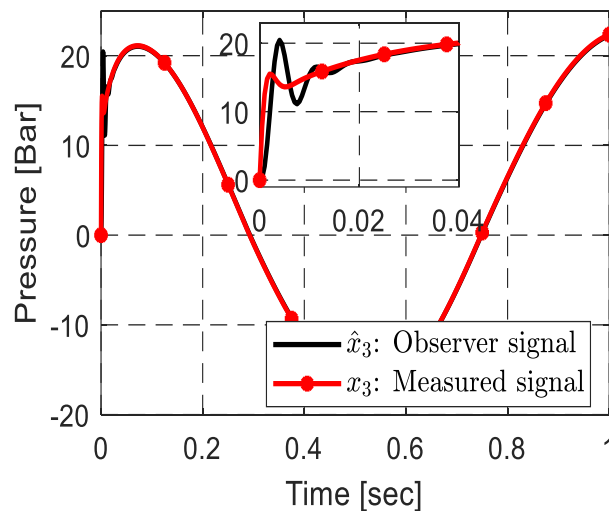*Figure 7. The control signal of sinusoidal reference trajectory signal for the noise free case.*

Figure 8. The sinusoidal reference trajectory tracking performance of the observer for the noise free case.
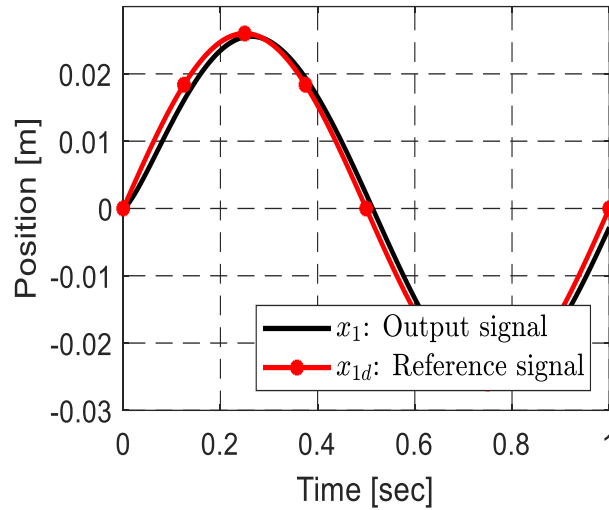
Figure 9. *The sinusoidal reference trajectory tracking performance of the PID controller for the noise free case.*
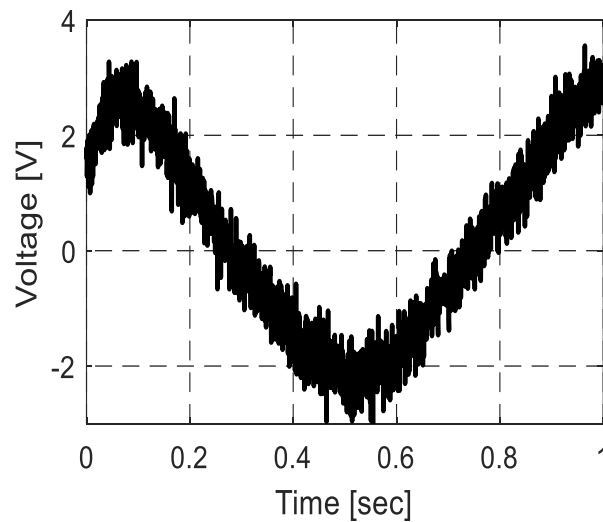

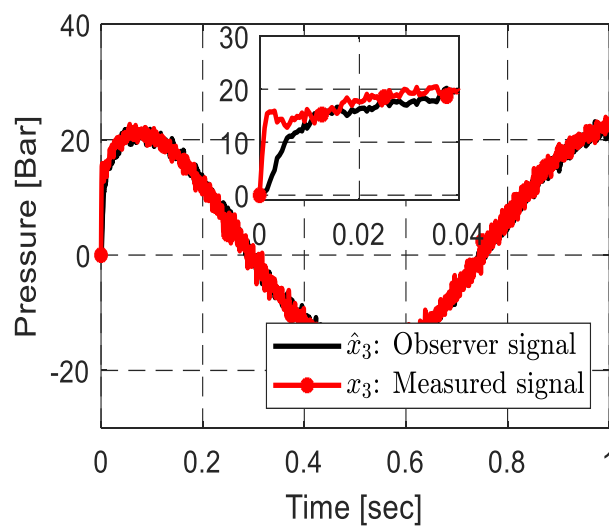**Figure 10.** *The control signal of sinusoidal reference trajectory signal for the noisy case.*

Figure 11. *The sinusoidal reference trajectory tracking performance of the observer for the noisy case.*
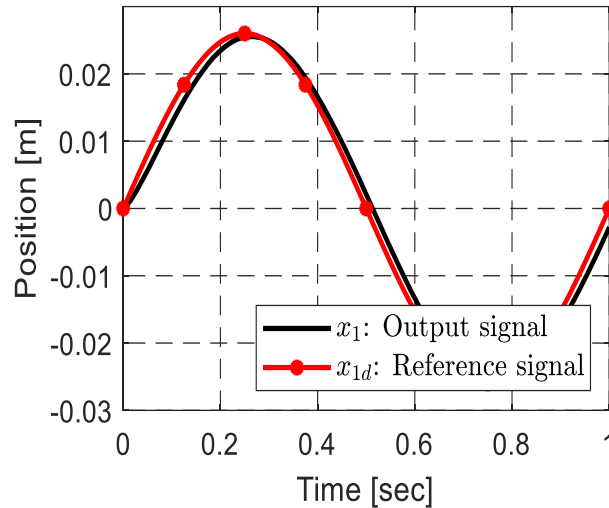
Figure 12. *The sinusoidal reference trajectory tracking performance of the PID controller for the noisy case.*

C. VARIABLE SET POINT TRACKING

The desired trajectory is selected as $x_{1d} = 0.005$ m and the desired trajectory changed to $x_{1d} = 0.0025$ m after 0.5 seconds. The initial values of all states are set to zero. The designed observer performance is tested in two different situations, noisy and noiseless. In both cases, the desired trajectory of the EHS has not been changed. The observer gains are selected as $\gamma = 5 * 10^{14}$ and $k_2 = 5$ for the noisy free cases and the observer gains are selected as $\gamma = 5 * 10^{10}$ and $k_2 = 500$ for the noisy cases. The control signal and the tracking performance of PID controller in both cases are given in Figures 13 and 15 and Figures 16 and 18, respectively for noisy free and noisy cases. The tracking performance of the observer is given in Figures 14 and 17 for the noise free case and the noisy case, respectively. From Figure 17, it is clear that the observer reaches the actual value quickly and successfully in the noise free case. From the Figure 17, it clear that the observer output tracks the shape of the actual signal successfully in the case of the noisy measurements.
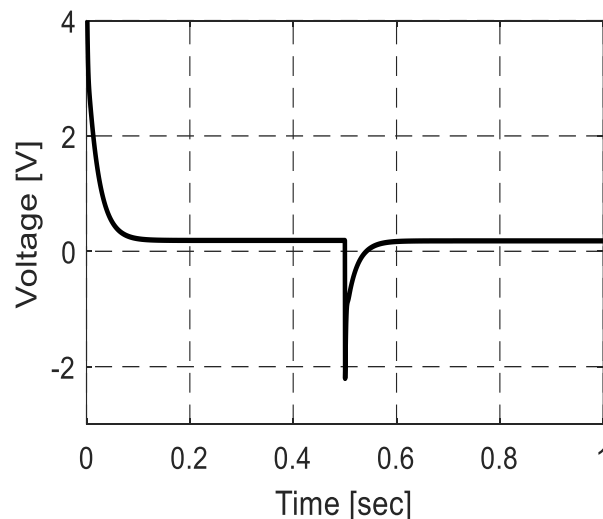

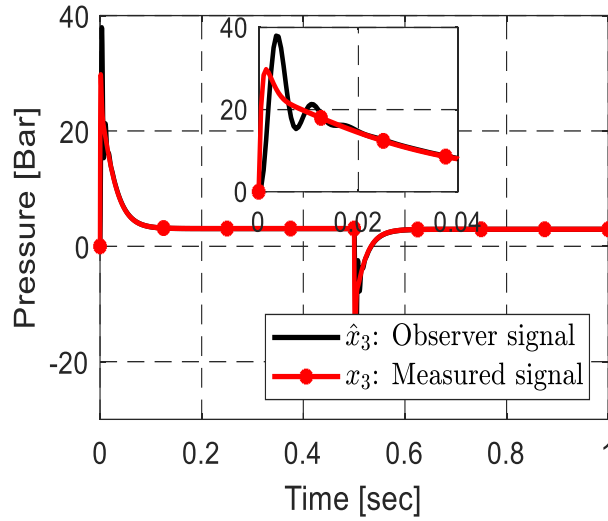**Figure 13.** *The control signal of variable set point tracking signal for the noise free case.*

Figure 14. *The variable set point tracking performance of the observer for the noise free case.*
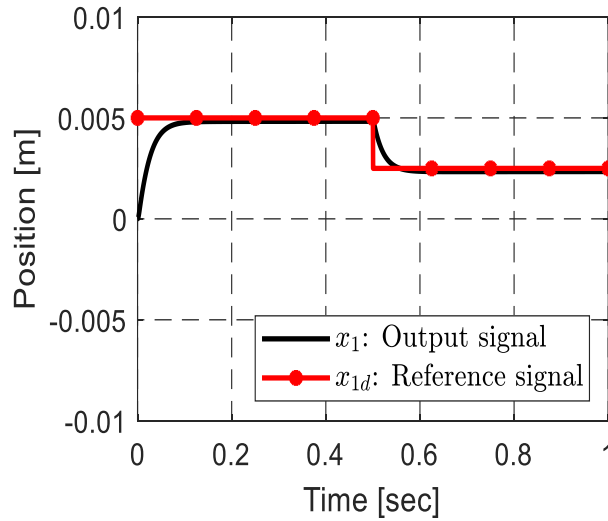

Figure 15. *The variable set point tracking performance of the PID controller for the noise free case.*
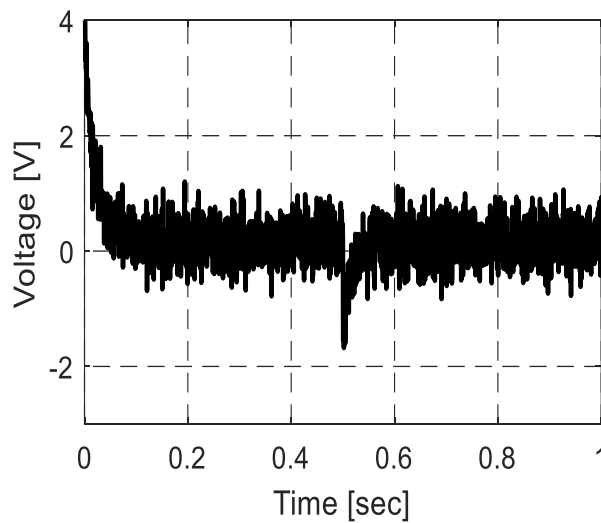

Figure 16. *The control signal of variable set point tracking signal for the noisy case.*
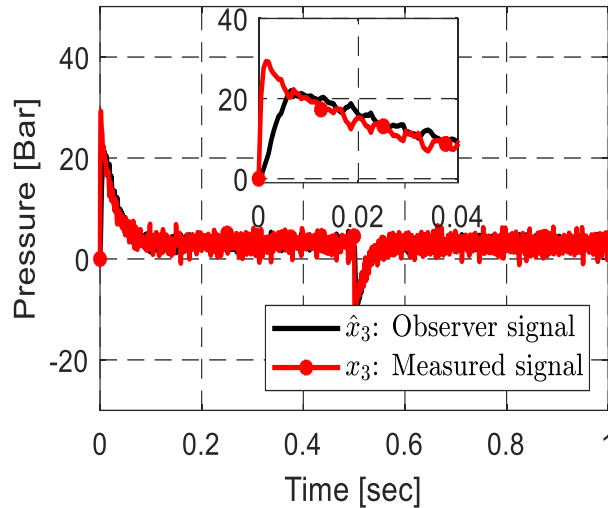
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Figure 17. The variable set point tracking performance of the observer for the noisy case.
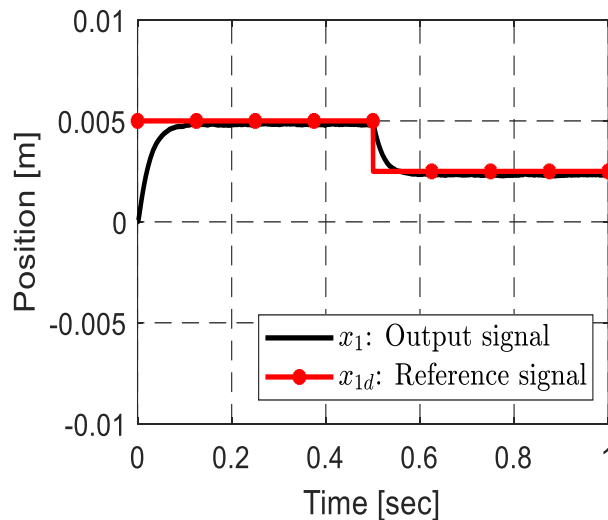

Figure 18. The variable set point tracking performance of the PID controller for the noisy case.

IV. DISCUSSION and CONCLUSION

In this paper, a Lyapunov based observer is proposed to observe the load pressure of the EHS. With the stability analysis, it is verified that observer error is proven to be around the origin, which can be set to be arbitrarily small. The performance of the observer is tested by the computational simulation studies which are conducted in MATLAB Simulink program. In the simulation studies, in order to prove the performance of the observer, the simulation results are presented with different reference tracking and in noisy and noise free cases. In the noisy cases, the state x_2 is exposed to the 30 dB additive white Gaussian noise. The simulation results demonstrated that the observer works efficiently in the noise free case and the noisy case.

V. KAYNAKLAR

[1]   Y. Chen, "Backstepping Controller Design for Electro-hydraulic Servo System with Sliding Observer," *Proceedings of the 29th Chinese Control Conference*, 29-31 July, Beijing, China, pp. 391-394, 2010.

[2]   J. Yao, Z. Jiao and D. Ma, "Extended-State-Observer-Based Output Feedback Nonlinear Robust Control of Hydraulic Systems with Backstepping," *IEEE Transaction on Industrial Electronics*, vol. 61, no. 11, pp. 6285-6293, 2014.

[3]   A. Chaji and S.K.H. Sani, "Observer Based Feedback Linearization Control for Electrohydraulic Servo Systems. International Congress on Technology," *Communication and Knowledge*, 11-12 November, Mashhad, Iran, pp, 226-231, 2015.

[4]   J. Yao, Z. Jiao and D. Ma, "Output Feedback Nonlinear Control for Electro-hydraulic Systems. *Mechatronics*," vol. 22, no. 6, pp, 766-777, 2012.

[5]   A. Monhanty and S. Gayaka, B. Yao, "An Adaptive Robust Observer for Velocity Estimation in an Electro-hydraulic System," *International Journal of Adaptive Control and Signal Processing*, vol. 26, no. 12, pp. 1076-108, 2012.

[6]   S.A. Ali, A. Christe, S. Begg and N. Langlois, "Continuous Discrete Time Observer Design for State and Disturbance Estimation of Electro-hydraulic Actuator Systems," *IEEE Transaction on Industrial Electronics*, vol. 63, no. 7, pp. 4314-4324, 2016.

[7]   Q. Guo, Y. Zhang, B. G. Celler and S. W. Su, "Backstepping Control of Electrohydraulic System Based on Extended-State Observer with Plant Dynamics Largely Unknown," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 11, pp. 6909-6920, 2016.

[8]   P. Nakkarat and S. Kuntanapreeda, "Observer-Based Backstepping Force Control of an Electrohydraulic Actuator," *Control Engineering Practice*, vol. 17, no. 8, pp. 895-902, 2009.

[9]   W. Kim, D. Won and C. C. Chung, "High Gain Observer Based Nonlinear Position Control for Electro-Hydraulic Servo Systems," *Proceeding of the 2010 American Control Conference*, 30 June-2 July, Baltimore, MD, USA, pp. 1140-1446, 2010.

[10]   Q. Guo, T. Yu and D. Jiang, "High-Gain Observer-Based Output Feedback Control of Single-rod Electro-hydraulic Actuator," *IET Control Theory & Applications*, vol. 9, no. 16, pp. 2395-2404, 2015.

[11]   W. Shen, H. Huang and J. Wang, "Robust Backstepping Sliding Mode Controller Investigation for a Port Plate Position Servo System Based on an Extended States Observer," *Asian Journal of Control*, vol. 21, no. 1, pp. 302-311, 2019.

[12]   S. Liu and B. Yao, "Sliding Mode Flow Rate Observer Design," *Proceeding of the 6th International Conference on Fluid Power Transmission and Control*, 5-8 April, Huangzhou, China, pp. 1-5, 2005.

[13]   A.A. Sofiane, "Sampled Data Observer Based Inter-Sample Output Predictor for Electrohydraulic Actuators," *ISA Transaction*, vol. 58, no. 1, pp. 421-433, 2015.

[14]   P. Garimella and B. Yao, "Nonlinear Adaptive Robust Observer Design for a Class of Nonlinear Systems," *Proceeding of the 2003 American Control Conference*, 4-6 June, Denver, CO, USA, pp. 4391-4396, 2003.

[15]   L. Schmidt, T. O. Andersan and H. C. Pedersen, "An Approach for State Observation in Dynamical Systems Based on the Twisting Algorithm," *IEEE International Conference on Mechatronics and Automation,* 4-7 August, Takamatsu, Japan, pp. 1051-1056, 2013.

[16]   Q. Zou, D. Chen and K. Wei, "Sliding Mode Based Mode Free Control of Electro-hydraulic System with Extended State Observer," *IEEE 5th Information Technology and Mechatronics Engineering Conference*, 12-14 June, Chongqing, China, pp. 1637-1641, 2020.

[17]   F. Lin, K. Ou and Y. Wang, "A Position Adaptive Control Associated with High Gain Observer for Electro-Hydraulic Servo System," *Chinese Automation Congress,* 6-8 November, Shanghai, China, pp. 3345-3350, 2020.

[18]   D. Won, W. Kim and M. Tomizuka, "Nonlinear Control with High Gain Extended State Observer for Position Tracking of Electro Hydraulic Systems," *IEEE/ASME Transactions on Mechatronics*, vol. 25, no. 6, pp. 2610-2621, 2020.

[19]   V. Phan, C. Vo, H. Dao and K. Ahn, "Robust Fault-Tolerant Control of an Electrohydraulic Actuator with a Novel Nonlinear Unknown Input Observer," *IEEE Access*, vol. 9, no. 1, 2021 pp. 30750-30760, 2021.

[20]   Q. Zou, "Extended State Observer-Based Finite Time Control of Electro-hydraulic System via Sliding Mode Technique," *Asian Journal of Control*, pp. 1-17, 2021.

[21]   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," *IEEE 56th Annual Conference on Decision and Control*, 12-15 December, Melbourne, VIC, Australia, pp. 3283-3288, 2017.

[22]   M. Onder, A. Bayrak, S. Aksoy "RISE-Based Backstepping Control Design for an Electro-Hydraulic Arm System with Parametric Uncertainties," *International Journal of Control*, pp. 1-14, 2021.