Lyapunov Based Observer Design for Electro-Hydraulic Arm System

Mithat ONDER a*, Alper BAYRAK a, Serkan AKSOY b

a Department of Electrical and Electronics Engineering, Faculty of Engineering, Bolu Abant Izzet Baysal University, Bolu, TURKEY
b Department of Electronics Engineering, Faculty of Engineering, Gebze Technical University, Kocaeli, TURKEY
* Corresponding author’s e-mail address: mithatonder@ibu.edu.tr
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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-Hidrolık Kol Sistemi için Lyapunov Tabanlı Gözlemci Tasarımı

ÖZ
Bu çalışmada, elektro-hidrolık 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 ayarlanabileceğini kararlanmıştır. Klasik PID denetleyicisi, elektro-hidrolık kol sisteminin konumunu kontrol etmek ve sistem durumlarınıändigil tutmak için kullanılmıştır. Önerilen gözlemcinin performansı, MATLAB Simulink programında yapılan hesaplama ve benzetimlerle değerlendirilmiştir. Gözlemcinin performansı iki durumda test edilmiştir: i) gürültüsüz durum ve ii) gürültülü durum. Gürültülü durumlarda, \( x_2 \) durumuna 30 dB ek beyaz Gauss gürültüsine maruz bırakılmıştır. Hesaplanan benzetim sonuçları, önerilen gözlemcinin hem gürültüsüz hem de gürültülü durumlarda verimli şekilde çalıştığını göstermektedir.

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

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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]:

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\[ \dot{x}_1 = x_2 \]
\[ \dot{x}_2 = \frac{1}{m} (-Kx_1 - bx_2 + A_px_3 - F_L) \]
\[ \dot{x}_3 = -\frac{4\beta_e A_p}{V_t} x_2 - \frac{4\beta_e C_{tl}}{V_t} x_3 + \frac{4\beta_e c_{dw} K_{sv}}{V_t \sqrt{p}} \sqrt{p_s - sgn(x_4)x_3} x_4 \]
\[ \dot{x}_4 = \frac{-x_4 + K_{sv} u}{T_{sv}} \]

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
\[ \dot{x}_3 = f(x_2, x_3, x_4) - \frac{4\beta_e C_{tl}}{V_t} x_3 \]

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.

| 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 |
| \( \beta_e \) | 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 |
| \( \rho \) | 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 begun 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 $\hat{x}_3$.

\[
\dot{x}_2 \triangleq x_2 - \hat{x}_2
\]  
where $\hat{x}_2$ is estimate of $x_2$.

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

\[
\dot{\hat{x}}_2 \triangleq x_2 - \dot{\hat{x}}_2
\]  
where $\dot{\hat{x}}_2$ is defined as follows,

\[
\dot{\hat{x}}_2 \triangleq -\frac{K}{m}x_1 - \frac{b}{m}\hat{x}_2 + \frac{A_p}{m}\hat{x}_3 - \frac{F}{m}.
\]  
where $\hat{x}_3$ is estimate of $x_3$.

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

\[
\dot{\hat{x}}_2 \triangleq -\frac{b}{m}\hat{x}_2 + \frac{A_p}{m}\hat{x}_3
\]  
where $\hat{x}_3$ is the observer error for $x_3$ and defined as:

\[
\hat{x}_3 \triangleq x_3 - \hat{x}_3.
\]

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

\[
\dot{\hat{x}}_3 \triangleq \gamma \frac{A_p}{m}\hat{x}_2 - k_2\hat{x}_3
\]  
where $\gamma \in \mathbb{R}^+$ and $k_2 \in \mathbb{R}^+$ are the observer gains and $k_2$ is defined as:

\[
k_2 \triangleq k_1 + \epsilon
\]  
where $k_1 \in \mathbb{R}^+$ and $\epsilon \in \mathbb{R}^+$ are constants. $|\epsilon| < k_1$ and $k_1$ is defined as:

\[
k_1 \triangleq \frac{4\beta e^{CT}}{V_t}
\]

It should be noted that $0 < \frac{4\beta e^{CT}}{V_t}$.

**C. STABILITY ANALYSIS**

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

\[
V = \frac{1}{2}x_2^2 + \frac{1}{2}\hat{x}_3^2.
\]  

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

\[
\dot{V} = \gamma \hat{x}_2\dot{\hat{x}}_2 + \hat{x}_3\dot{\hat{x}}_3.
\]  

By substituting (3), (6), (8) and using (10) and the time derivative of (7), (12) can be rewritten as:
\[ \dot{V} = -\frac{b}{m} \gamma \ddot{x}_2^2 + \ddot{x}_3 \left( \frac{A_p}{m} \gamma \dot{x}_2 + f(x_2, x_3, x_4) - k_1 x_3 - \gamma \frac{A_p}{m} \ddot{x}_2 + k_2 \ddot{x}_3. \tag{13} \]

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

\[ \dot{V} = -\frac{b}{m} \gamma \ddot{x}_2^2 + \ddot{x}_3 f(x_2, x_3, x_4) - k_2 \ddot{x}_3 + \ddot{x}_3 x_3 \tag{14} \]

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:

\[ \dot{V} < -\frac{b}{m} \gamma \ddot{x}_2^2 - k_2 \ddot{x}_3^2 + |\ddot{x}_3| |f| + |\ddot{x}_3| |\epsilon||x_3| \]
\[ < -\frac{b}{m} \gamma \ddot{x}_2^2 - k_2 \ddot{x}_3^2 + |\ddot{x}_3| \xi \tag{15} \]

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:

\[ \dot{V} < -\frac{b}{m} \gamma \ddot{x}_2^2 - \ddot{x}_3^2 - (\sqrt{k_2 - 1} |\ddot{x}_3| - \frac{1}{2 \sqrt{k_2 - 1}} \xi)^2 + \frac{1}{4(k_2 - 1)} \xi^2 \]
\[ < -\frac{b}{m} \gamma \ddot{x}_2^2 - \ddot{x}_3^2 + \frac{1}{4(k_2 - 1)} \xi^2. \tag{18} \]

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

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

where

\[ w = \min \left( \frac{b}{m} \gamma, 1 \right) \tag{20} \]
\[ k_2 > 1 \tag{21} \]
\[ z = [\ddot{x}_2 \ \ddot{x}_3]^T \tag{22} \]
\[ \psi = \frac{1}{4(k_2 - 1)} \xi^2. \tag{23} \]

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 \( \ddot{x}_3 \), 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          |
| $C_{tt}$  | 2.5*10^-11  | m^3/(s, Pa) |
| $w$       | 0.024       | m            |
| $A_p$     | 2.01        | cm^2         |
| $\beta_e$ | 2*10^8      | Pa           |
| $T_{sv}$  | 12          | ms           |
| $b$       | 2500        | N.s/m        |
| $\rho$   | 850         | kg/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,

$$u = K_p e + K_d \dot{e} + K_i \int e$$  \hspace{1cm} (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 $\gamma = 5 \times 10^{14}$ and $k_2 = 5$ for the noisy free cases and the observer gains are selected as $\gamma = 5 \times 10^{10}$ 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 $\gamma = 5 \times 10^{14}$ and $k_2 = 5$ for the noisy free cases and the observer gains are selected as $\gamma = 5 \times 10^{10}$ 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.
The desired trajectory is selected as $x_{td} = 26.10^{-3}\sin(2\pi t) \text{m}$. 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 $\gamma = 5 \times 10^{14}$ and $k_2 = 5$ for the noisy free cases and the observer gains are selected as $\gamma = 5 \times 10^{10}$ 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.
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 $\gamma = 5 \times 10^{14}$ and $k_2 = 5$ for the noisy free cases and the observer gains are selected as $\gamma = 5 \times 10^{10}$ 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 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.
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.

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