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An Alternative Nonlinear Lyapunov Redesign Velocity Controller for an Electrohydraulic Drive

Honorine Angue Mintsa [1,*], Gérémino Ella Eny [2], Nzamba Senouveau [3], Jean-Pierre Kenné [4], Rolland Michel Assoumou Nzué [5]
[1, 5] Department of Mechanical Engineering, Polytechnic School of Masuku, University of Science and Technology of Masuku (USTM), Franceville, Gabon
[2] Department of Physics, Faculty of Sciences, University of Science and Technology of Masuku (USTM), Franceville, Gabon
[3] Department of Electrical Engineering, Polytechnic School of Masuku, University of Science and Technology of Masuku (USTM), Franceville, Gabon
[4] Ecole de Technologie Supérieure (ETS), University of Quebec, Montreal, QC H3C 1K3, Canada
Email: [1] anguemintsa_honorine@yahoo.fr, [2] ellaenyg@yahoo.fr, [3] senouveau@yahoo.fr, [4] jean-pierre.kenne@etsmtl.ca, [5] rollandassoumou82@gmail.com
*Corresponding Author

Abstract—**This research aims at developing control law strategies that improve the performances and the robustness of electrohydraulic servosystems (EHSS) operation while considering easy implementation. To address the strongly nonlinear nature of the EHSS, a number of control algorithms based on backstepping approach is intensively used in the literature. The main contribution of this paper is to consider an alternative approach to synthetize a Lyapunov redesign nonlinear EHSS velocity controller. The proposed control law design is based on an appropriate choice of the control lyapunov function (clf), the extension of the Sontag formula and the construction of a nonlinear observer. The clf includes all the three system variable states in a positive define function. The Sontag formula is used in the time derivative of our clf in order to ensure an asymptotic stabilizing controller for regulating and tracking objectives. A nonlinear observer is developed in order to bring to the proposed controller the estimated values of the first and the second time output derivatives. The design, the tuning implementation and the performances of the proposed controller are compared to those of its equivalent backstepping controller. It is shown that the proposed controller is easier to design with simple implementation tuning while the backstepping controller has several complex design steps and implementation tuning issue. Moreover, the best performances especially under disturbance in the viscous damping are achieved with the proposed controller.**

Keywords—Control Lyapunov Function; Lyapunov Redesign; Sontag's formula; Backstepping Control; Nonlinear Observer; Electrohydraulic System.

I. Introduction

Electrohydraulic systems use pressurized oil to accomplish mechanical work. Because the oil is incompressible, these power systems are selected to manipulate large loads with accuracy, rapidity and robustness. Common engineering applications include automobile suspension [1], [2], automobile power steering [3], [4], robotic actuation [5], [6], aerospace actuation [7], [8],[9] machine tool [10], [11], press actuation [12] and injection molding machine [13]. The PID control laws are widely used in industrial Electro-Hydraulic Servo-System (EHSS) because this linear control theory is well known, simple and easy to implement [14]. However, the EHSS has a strongly nonlinear dynamics [15]. It starts with the square-root relationship between the flow and the pressure difference across the actuator lines [16]. Inside the square-root, the sign function indicates the direction of flow across the hydraulic drive and adds discontinuity. Moreover, the parameters of the EHSS dynamics are affected by the temperature, the air insertion and others disturbances making the system close to instability [17]. Therefore, the classical PID controller does not maintain the performances over a wide range of operating points. In order to improve the performances, researchers use optimization tools [18], [19], [20], artificial intelligence approaches [21], [22], [23], nonlinear functions [24] to tune the three PID gains. These parameters tuning strategies lead to very complex and expensive closed loop systems with implementation issues [25].

Lyapunov redesign is a powerful control strategy that deals with nonlinear systems. It consists of constructing an asymptotic stabilizing control law while using a Lyapunov control function (clf) [26], [27], [28]. A clf is a positive define function that includes all the system state variables and which the time derivative is made negative by choosing a particular control law. In the EHSS literature, backstepping approach is by far the most Lyapunov redesign control widely used [29], [30], [31]. In this approach, the system is dismembered in 1rst order subsystems and the clf is recursively constructed through virtual controls. Researchers combine this approach with adaptive control [32], sliding mode control [33], neural networks [34], [35]. However, common EHSS system order varies between three and five [36], [37]. These high orders in the recursive clf construction cause an explosion of complexity.

Based on the Artstein's results [27], Sontag [28] constructs a different Lyapunov redesign control architecture based on Ricatti solution equation from a system's clf expressed in terms of Lie derivatives. Unlike the recursive Lyapunov redesign, the approach based on Sontag formula offers possibilities of deducing simple Lyapunov redesign control laws. However, for now, this approach is restricted to nonlinear systems that is affine in control [38]. Authors [39] [40] shows that the Sontag formula feedback control ensure

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the design of asymptotic stabilizing controller while minimizes the cost function. Researchers [41] extend the Sontag formula to obtain an event-based feedback between two sampling times, they use the time derivative of a smooth clf for their event function. In [42], the Sontag formula is used to design a ship position controller in presence of state input constrained. At the end of the Sontag formula literature, we notice that this approach is mainly used for regulating objectives. Moreover, to our knowledge, the Sontag's control formula applied to EHSS is not yet available in the literature. Thus, this motivates us to investigate the Sontag formula performances in the EHSS regulating and tracking velocity problems.

The main research contributions of this paper are listed below:

- An alternative lyapunov redesign control approach other than backstepping is brought in the EHSS velocity control literature;
- The proposed controller is based on Sontag formula that we extend to the tracking version with a nonlinear observer based on the exponential observer developed in [26] and the Luenberger like nonlinear observer [43];
- The design and the implementation tuning of the proposed controller are compared to those of its equivalent Lyapunov redesign backstepping controller (known to have implementation issue [44]). It is shown that the proposed one generates less design and tuning effort.
- The performances of the proposed controller are compare to those of the Lyapunov redesign backstepping. It is shown that the proposed controller demonstrate the best results especially under viscous damping disturbance.

Fig. 1 illustrates the approach used to synthetize the two-velocity redesign Lyapunov controllers in the paper. It is shown that the proposed controller has an additional step where a nonlinear observer is developed.

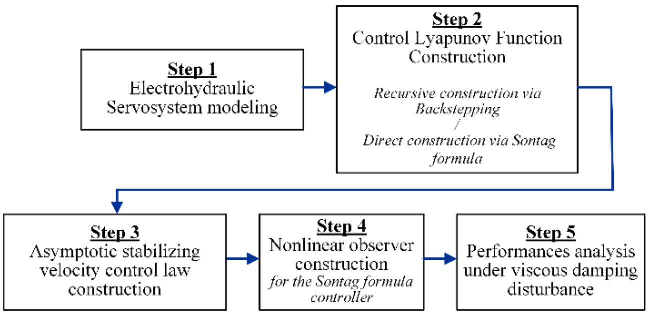

Fig. 1. Lyapunov Redesign methodology for both controllers used in the paper

The paper is organized as follows: section II describes the mathematical models of the EHSS under study. Section III shows the derivation of the proposed control law based on the Sontag's formula. Section IV depicts the design of the Lyapunov design backstepping controller. In section V, the comparison between the two controllers is discussed. In section VI, the simulation results are given and analysed using matlab/Simulink environment. Finally, Section VII is devoted to the conclusion.

II. SYSTEM MODELINGS AND REFERENCE MODEL

This section is devoted to the modeling of the EHSS under study. A state space form and a controllability canonical form are performed in order to facilitate the design of the backsteping controller and the proposed based Sontag formula controller [45] respectively. A the end of the section, a reference model is constructed to provide the useful desired transient performances to the proposed controller [46] .

The EHSS under consideration is shown in Fig. 2. The hydraulic oil stored in the tank is sent to the system by the positive fixed displacement pump. The relief valve and the oleo pneumatic accumulator maintain constant the inlet pressure P_s of the electrohydraulic servovalve. The electrical control input u(t) acts on the servovalve opening aera by moving the valve spool. By changing the value of the servovalve opening aera, a pressure difference $P_L(t)$ across the hydraulic motor lines is created and the mechanical load is driven. A sensor measures the velocity $\dot{\theta}(t)$ of the mechanical load that is the output signal of this study.

A. State Space EHSS System Modeling

The readers are referred to our previous works [47], [48], [49] and to Merritt [15] for the details about the EHSS nonlinear state-space model under study and the sigmoid function. A third order nonlinear state space model is described by (1). As one can see, the non differentiable sign function is approximated by the differentiable sigmoid function.

$$\dot{x}_1(t) = \frac{d_m}{J}x_2(t) - \frac{B_m}{J}x_1(t)$$

$$\dot{x}_2(t) = \frac{4\beta c_d}{V_m}\left(x_3(t)\frac{c_d}{\sqrt{\rho}}\sqrt{P_s - sigm\big(x_3(t)\big)x_2(t)} - d_m x_1(t) - c_{sm}x_2(t)\right)$$

$$\dot{x}_3(t) = \frac{K}{\tau}u(t) - \frac{1}{\tau}x_3(t)$$

$$y(t) = x_1(t) \tag{1}$$

$$sign\big(x(t)\big) \simeq sigm\big(x(t)\big) = \frac{1 - e^{-\delta x(t)}}{1 + e^{-\delta x(t)}} \tag{2}$$

where, $x_1(t)$is the angular velocity, $x_2(t)$ is the motor pressure difference due to the load, $x_3(t)$ is the servovalve opening area due to the input signal, $u(t)$ is the control current input, J is the hydraulic motor total inertia, d_m is the volumetric displacement of the motor, β is the fluid bulk modulus, V_m is the total oil volume of the hydraulic motor, c_d is the servovalve discharge coefficient, ρ is the fluid mass density, c_{sm} is the leakage coefficient of the hydraulic motor, P_s is the supply pressure at the inlet of the servovalve, K is the servovalve amplifier gain, τ is the servovalve time constant.

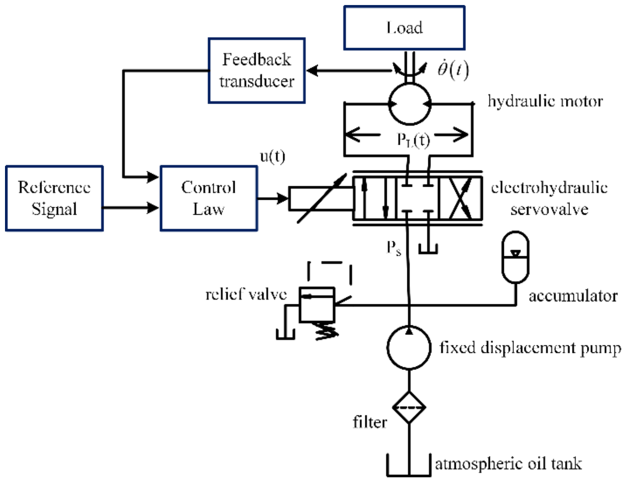

Fig. 2. Electrohydraulic Servo System

It is noted that the model under study keeps the strong nonlinearity of the flow expression. In order to avoid the sign function and the square-root in the flow pressure relationship, the linearized version of flow expression is used in the EHSS backstepping literature [50], [51] .

B. EHSS System Modeling in a Companion Form

In order to put the EHSS in the affine control form by using the input output relationship, we have to differentiate the output until the control input appears. The time derivative of the continuous sigmoid function is approximated to 0 as explained in [52]. Then after three time-differentiations of the output $y(t)$, we obtain the output-input relationship as shown in equation (3).

$$\dddot{y}(t) = \sum_{i=1}^{6} a_i f_i\,(x,t) + g(x,t)u(t) \tag{3}$$

where

$$g(x,t) = \frac{4\beta D_m c_d K}{J\tau V_m\sqrt{\rho}}\sqrt{P_s - x_2(t)sigm(x_3(t))}$$

$$f_1(x,t) = x_1(t)$$

$$f_2(x,t) = x_2(t)$$

$$f_3(x,t) = x_3(t)\sqrt{P_s - x_2(t)sigm(x_3(t))}$$

$$f_4(x,t) = x_3(t)x_3(t)sigm(x_3(t))$$

$$f_5(x,t) = \frac{x_1(t)x_3(t)sigm(x_3(t))}{\sqrt{P_s - x_2(t)sigm(x_3(t))}}$$

$$f_6(x,t) = \frac{x_2(t)x_3(t)sigm(x_3(t))}{\sqrt{P_s - x_2(t)sigm(x_3(t))}}$$

$$a_1 = \frac{8\beta B d_m^2 J V_m - B^3 V_m^2 + 16\beta^2 d_m^2 c_{sm} J^2}{J^3 V_m^2}$$

$$a_2 = \frac{B^2 V_m^2 d_m - 4\beta d_m^3 J V_m + 16\beta^2 d_m c_{sm}^2 J^2 + 4\beta B d_m V_m c_{sm} J}{J^3 V_m^2}$$

$$a_3 = -\frac{\tau(16\beta^2 c_d d_m c_{sm} J + 4\beta c_d B d_m V_m) + 4\beta d_m c_d J V_m}{\tau J^2 V_m^2 \sqrt{\rho}}$$

$$a_4 = -\frac{8\beta^2 d_m c_d^2}{J V_m^2 \rho}$$

$$a_5 = \frac{8\beta^2 d_m c_d c_{sm}}{J V_m^2 \sqrt{\rho}}$$

$$a_6 = \frac{8\beta^2 d_m c_d c_{sm}}{J V_m^2 \sqrt{\rho}}$$

It is noted that the function $g(x,t)$ is always strictly positive because the pressure difference across the motor line never exceeds $\frac{2P_s}{3}$ for the servovalve requirements [15], [53]. Thus, we obtain (4).

$$\frac{4\beta D_m c_d K}{J\tau V_m\sqrt{\rho}}\sqrt{\frac{P_s}{3}} \le g(x,t) \le \frac{4\beta D_m c_d K}{J\tau V_m\sqrt{\rho}}\sqrt{P_s} \tag{4}$$

One can note that is not easy to put the EHSS in a companion form and one advantage of the backstepping is to be performed using the state space model form [54].

C. Reference Model

As we found the control input after differentiating three times the output, the three order EHSS under study has no zero dynamics [55]. Thus, a three-order reference model shown in (5) is given in order to monitor the trajectory of the output signal.

$$\dddot{y}_{des}(t) + \alpha_2\ddot{y}_{des}(t) + \alpha_1\dot{y}_{des}(t) + \alpha_0 y_{des}(t) = r(t) \tag{5}$$

where $y_{des}(t)$ and $r(t)$are the desired output and the input of the reference model respectively. The coefficient $\alpha_i$are distributed in the Butterworth pattern.

III. The Nonlinear Controller Design Based on Sontag Formula

This section presents the design of the proposed control law based on the Sontag's formula [26], [28]. Before starting, we summarize the most important Sontag results [56]:

Result 1: *A smooth positive define and radially unbounded function V_s: $\mathbb{R}^n \to \mathbb{R}_+$ is called a control Lyapunov function (clf) for the affine in control system$\dot{x}_s(t) = f_s(x,t) + g_s(x,t)u(t)$ if,*

$$\frac{\partial V_s(x_s(t))}{\partial x_s} f_s(x(t)) + \frac{\partial V_s(x_s(t))}{\partial x_s} g_s(x_s(t))u_s(t) < 0,\ \forall x_s \neq 0.$$

Result 2: if the system $\dot{x}_s(t) = f_s(x_s,t) + g(x_s,t)u_s(t)$ *admits as V_s a clf then a asymptotic stabilizing Lyapunov redesign control law u(t) for $\forall x \neq 0$ as in (6).*

$$u_s(t) = \begin{cases} -\dfrac{\frac{\partial V_s}{\partial x} f_s + \sqrt{\left(\frac{\partial V_s}{\partial x} f_s\right)^2 + \left(\frac{\partial V_s}{\partial x} g_s\right)^4}}{\frac{\partial V_s}{\partial x} g_s} & , \frac{\partial V_s}{\partial x} g_s \neq 0 \\ 0 & , \frac{\partial V_s}{\partial x} g_s = 0 \end{cases} \tag{6}$$

A. The Proposed Control Lyapunov Function

The design of the proposed controller starts with the choice of a positive define and unbounded function that includes all the state variables. Equation (7) is a quadratic function of $s(x,t)$ which is a weighted sum of the velocity error and its derivatives up to order 2. According to Slotine and Li [57], the advantage of this combined output error is to replace the tracking problem of the third order system in $x(t)$by a first order system in $s(x,t)$.

$$V(x,t) = \frac{s^2(x,t)}{2} \tag{7}$$

where $s(x,t) = \ddot{e}(t) + \lambda_1 \dot{e}(t) + \lambda_0 e(t)$ is the combined error or the weighted sum of the velocity error $e(t) = y(t) - y_{des}(t)$. The coefficient λ_i are distributed in the Butterworth pattern. The derivative of the function $V(x,t)$ gives (8) where the input control signal appears:

$$\dot{V}(x,t) = \frac{\partial V}{\partial s}\dot{s} \tag{8}$$

$$\dot{V}(x,t) = \frac{\partial V}{\partial s}\left(\sum_{i=1}^{6} a_i f_i(x,t) + g(x,t)u(t) - \dddot{y}_{des} + \lambda_1 \ddot{e}(t) + \lambda_0 \dot{e}(t)\right) \tag{9}$$

It is noted that this clf is smooth for $\forall s(x,t) \neq 0$ *instead of x(t)*. Moreover, in contrast with the original Sontag control Lyapunov function, our clf has the tracking error dynamics as the control goal is to track the desired trajectory of the reference model. Therefore, regulation ($\dot{e}(t) = \dot{y}(t)$) and tracking problems are considered with the proposed design [58].

B. The Proposed Nonlinear Controller

Next, we extend the Sontag's formula (6) with the reference model and the combined error. Considering $\frac{\partial V}{\partial s} g \neq 0 \rightarrow s(x,t) \neq 0$, We obtain the control law (10).

$$u(t) = \begin{cases} -\dfrac{\frac{\partial V}{\partial s}\left(\sum_{i=1}^{6} a_i f_i(x,t) - \dddot{y}_{des} + \lambda_1 \ddot{e}(t) + \lambda_0 \dot{e}(t)\right) + \sqrt{\left(\frac{\partial V}{\partial s}\sum_{i=1}^{6} a_i f_i(x,t)\right)^2 + \left(\frac{\partial V}{\partial s} g(x,t)\right)^4}}{\frac{\partial V}{\partial s} g} & , s(x,t) \neq 0 \\ 0 & , s(x,t) = 0 \end{cases} \tag{10}$$

Which yields to

$$\dot{V}(x,t) = -\sqrt{\left(\frac{\partial V}{\partial s}\sum_{i=1}^{6} a_i f_i(x,t)\right)^2 + \left(\frac{\partial V}{\partial s} g(x,t)\right)^4} \tag{11}$$

As desired. Moreover, considering (4) and (11), we have

$$\dot{V}(x,t) = \begin{cases} < 0 & if \quad s(x,t) \neq 0 \\ = 0 & if \quad s(x,t) = 0 \end{cases} \tag{12}$$

Equation (12) shows that the time derivative of V (x, t) is negative define. Hence, the controlled system is asymptotically stable. $s(x,t)$ goes to zero as t tends to infinity, which implies that the tracking error and its time derivatives up to order 2 go to zero as time goes to infinity. Moreover, because the function $g(x,t)$ is always positive, a further writing of the control law gives (13). Where in equation (13), $F(x,t) = \sum_{i=1}^{6} a_i f_i(x,t) - \dddot{y}_{des} + \lambda_1 \ddot{e}(t) + \lambda_0 \dot{e}(t)$. One can see that this control law is a sliding mode controller with an equivalent control coming from the inverse dynamics [59]. We replaced the sign function by the sigmoid function in (13) in order to avoid discontinuous signal and chattering phenomenon [60], [50].

$$u(t) = \begin{cases} -\dfrac{1}{g(x,t)}\left(F(x,t) + sigm\big(s(t)\big)\sqrt{\big(F(x,t)\big)^2 + \left(\frac{\partial V}{\partial s}\right)^2 \big(g(x,t)\big)^4}\right) & , s(x,t) \neq 0 \\ 0 & , s(x,t) = 0 \end{cases} \tag{13}$$

C. The Proposed Nonlinear Observer Design

We assume that all the state variables of the EHSS are available which are $x_1(t)$,$x_2(t)$,$x_3(t)$,$x_4(t)$. However, the first and the second time derivatives of the output are not available. To address this implementation issue, we propose a nonlinear observer that is a variation of the one developed in [26], [43] and [61]. We start by reorganizing the model in a linear / nonlinear separated parts near to the affine in control form [62]. We obtain (14)-(15).

$$\begin{bmatrix} \dot{x}_{o1}(t) \\ \dot{x}_{o2}(t) \\ \dot{x}_{o3}(t) \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -a_{y_1} & -a_{y_2} & -a_{y_3} \end{bmatrix}}_{A_O} \begin{bmatrix} x_{o1}(t) \\ x_{o2}(t) \\ x_{o3}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ g(x,t) \end{bmatrix} u(t) + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} f_o(x,t) \tag{14}$$

$$y(t) = \underbrace{\begin{bmatrix} 1 & 0 & 0 \end{bmatrix}}_{C_o^T} \begin{bmatrix} x_{o1}(t) \\ x_{o2}(t) \\ x_{o3}(t) \end{bmatrix} \tag{15}$$

with,

$$a_{y0} = \frac{4\beta B c_{sm} J + 4\beta d_m^2 J}{\tau J^2 V_m}$$

$$a_{y1} = \frac{4\beta d_m^2 J + 4\beta c_{sm} J B}{J^2 V_m} + \frac{B V_m + 4\beta c_{sm} J}{\tau J V_m}$$

$$a_{y2} = \frac{4\beta c_{sm} J + B V_m}{J V_m} + \frac{1}{\tau}$$

The new state variables are chosen as $x_{o1}(t) = y(t)$, $x_{o2}(t) = \dot{y}(t)$ and $x_{o3}(t) = \ddot{y}(t)$. An exponential observer for (14)-(15), where $\hat{x}_{oi}(t)$ and $\hat{y}(t)$are the estimated of $x_{oi}(t)$ and $y(t)$respectively, is

$$\dot{\hat{x}}_o(t) = A_o \dot{\hat{x}}_o(t) + K_{po}\big(y(t) - \hat{y}(t)\big) + \begin{bmatrix} 0 \\ 0 \\ g(x,t) \end{bmatrix} u(t) + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} f_o(x,t)$$

$$\hat{y}(t) = C_o^T \begin{bmatrix} \hat{x}_{1o}(t) \\ \hat{x}_{2o}(t) \\ \hat{x}_{3o}(t) \end{bmatrix} \tag{16}$$

where the vector K_{po} is chosen so that the total matrix $A_{oy} = A_o - K_{po} C_o^T$ is Hurwitz which yields to the exponentially decay of the observation error $e_{obs}(t) = x_{o1}(t) - \hat{x}_{o1}(t)$ as shown in (17).

$$e_{obs}(t) = A_{oy} e_{obs}(t) \tag{17}$$

As the convergence to zero is exponential, we neglect the effect of the observation error as is often done in linear systems [63] and some nonlinear systems [64], [65]. Fig. 3 shows the block diagram of the EHSS closed loop system where the two steps of the proposed controller and the nonlinear observer are visible.

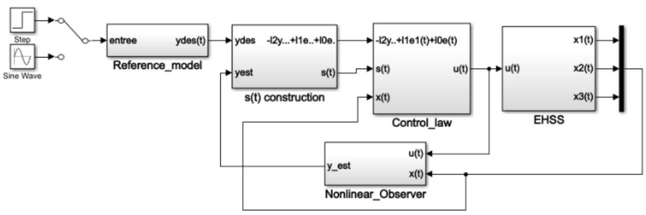

Fig. 3. EHSS closed loop block diagram with the proposed controller

IV. THE BACKSTEPPING CONTROLLER

In this section, the backstepping redesign Lyapunov is synthetized in order to compare its design, its implementation and its performance results with the proposed law. The present design follows the classical backstepping control steps [66], [67], [68]. Since the EHSS state space model has three state variables, the design is articulated around three steps corresponding to the three subsystems. We introduce the tracking error $e_i(t) = x_i(t) - x_{id}(t)$ where $x_{id}(t)$is the desired state.

A. Step 1: The First Virtual Control for the First Subsystem

Consider the first subsystem $\dot{x}_1(t) = \frac{d_m}{J} x_2(t)$-$\frac{B_m}{J} x_1(t)$. Choose the first candidate Lyapunov function for this subsystem as (18).

$$V_1(t) = \frac{1}{2} e_1^2(t) \tag{18}$$

The time derivative of this Lyapunov function gives as (19).

$$\dot{V}_1(t) = e_1(t)\left(\frac{d_m}{J} e_2(t) + \frac{d_m}{J} x_{2d}(t) - \frac{b_m}{J} e_1(t) - \frac{b_m}{J} x_{1d}(t) - \dot{x}_{1d}\right) \tag{19}$$

If we choose $x_{2d}(t)$ as the first virtual control such that (20).

$$x_{2d}(t) = \frac{J}{d_m}\left(\frac{b_m}{J} x_{1d}(t) + \dot{x}_{1d} - k_1 e_1(t)\right) \tag{20}$$

where $k_1 > 0$, we obtain as (21).

$$\dot{V}_1(t) = -\left(\frac{b_m}{J} + k_1\right) e_1^2(t) + \frac{d_m}{J} e_2(t) e_1(t) \tag{21}$$

B. Step 2: The Second Virtual Control

Now, consider the second subsystem $\dot{x}_2(t) = \frac{4\beta c_d}{V_m}\left(x_3(t) \frac{c_d}{\sqrt{\rho}} \sqrt{P_s\text{-}sigm\big(x_3(t)\big) x_2(t)}\text{-}d_m x_1(t)\text{-}c_{sm} x_2(t)\right)$. Choose the second candidate Lyapunov function for this subsystem as (22).

$$V_2(t) = \frac{1}{2} e_1^2(t) + \frac{1}{2} e_2^2(t) \tag{22}$$

The time derivative of this Lyapunov function gives in (23).

$$\dot{V}_2(t) = -\left(\frac{b_m}{J} + k_1\right) e_1^2(t) + e_2(t)\left(\begin{aligned} &\frac{d_m}{J} e_1(t) + \frac{4\beta c_d}{v_m\sqrt{\rho}} e_3(t)\sqrt{P_s - sign\big(x_3(t)\big) x_2(t)} \\ &+ \frac{4\beta c_d}{v_m\sqrt{\rho}} x_{3d}(t)\sqrt{P_s - sign\big(x_3(t)\big) x_2(t)} - \frac{4\beta d_m}{v_m} x_1(t) - \frac{4\beta c_{sm}}{v_m} x_2(t) - \dot{x}_{2d}(t) \end{aligned}\right) \tag{23}$$

If we choose $x_{3d}(t)$ as the second virtual control such that (24).

$$x_{3d}(t) = \frac{v_m\sqrt{\rho}}{4\beta c_d\sqrt{P_s - sigm\big(x_3(t)\big) x_2(t)}}\left(\begin{aligned} &-\frac{d_m}{J} e_1(t) + \frac{4\beta d_m}{v_m} x_1(t) \\ &+ \frac{4\beta c_{sm}}{v_m} x_{2d}(t) + \dot{x}_{2d}(t) - k_2 e_2(t) \end{aligned}\right) \tag{24}$$

where $k_2 > 0$, we obtain as (25).

$$\dot{V}_2(t) = -\left(\frac{b_m}{J} + k_1\right) e_1^2(t) - \left(\frac{4\beta c_{sm}}{v_m} + k_2\right) e_2^2(t) + \frac{4\beta c_d}{v_m\sqrt{\rho}} e_2(t) e_3(t)\sqrt{P_s - sign\big(x_3(t)\big) x_2(t)} \tag{25}$$

C. Step 3: The Deducing Nonlinear Backstepping Controller

Finally, consider the third subsystem $\dot{x}_3(t) = \frac{K}{\tau} u(t) - \frac{1}{\tau} x_3(t)$ Choose the final candidate Lyapunov function for this subsystem as (26).

$$V_3(t) = \frac{1}{2} e_1^2(t) + \frac{1}{2} e_2^2(t) + \frac{1}{2} e_2^3(t) \tag{26}$$

The time derivative of this Lyapunov function gives as (27).

$$\dot{V}_3(t) = -\left(\frac{b_m}{J}+k_1\right)e_1^2(t) - \left(\frac{4\beta c_{sm}}{v_m}+k_2\right)e_2^2(t) + e_3(t)\begin{pmatrix} \frac{4\beta c_d}{v_m\sqrt{\rho}}e_2(t)\sqrt{P_s - sign(x_3(t))x_2(t)} + \frac{K}{\tau}u(t) \\ -\frac{1}{\tau}e_3(t) + \frac{1}{\tau}x_{3d}(t) - \dot{x}_{3d}(t) \end{pmatrix} \quad (27)$$

If we choose the control signal $u(t)$ such that (28).

$$u(t) = \frac{\tau}{K}\left(\frac{1}{\tau}x_{3d}(t) + \dot{x}_{3d}(t) - \frac{4\beta c_d}{v_m\sqrt{\rho}}e_2(t)\sqrt{P_s - sigm(x_3(t))x_2(t)} - k_3 e_3(t)\right) \quad (28)$$

where $k_3 > 0$, we obtain (29).

$$\dot{V}_3(t) = -\left(\frac{b_m}{J}+k_1\right)e_1^2(t) - \left(\frac{4\beta c_{sm}}{v_m}+k_2\right)e_2^2(t) - \left(\frac{1}{\tau}+k_3\right)e_3^2(t) \quad (29)$$

Thus, the deducing Lyapunov function is negative define ensuring the asymptotic stability. Fig. 4 shows the implementation of the backstepping controller in matlab/Simulink where the three steps are highlighted.

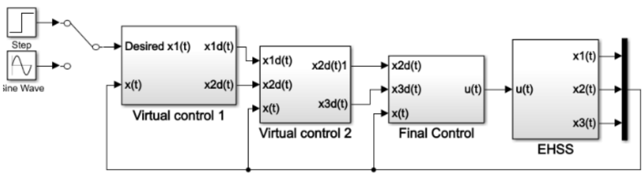

Fig. 4. EHSS closed loop block diagram with the backstepping controller

V. Design and Tuning Discution

In this section, the design, the implementation and the performances of both controllers are analysed and compared. One can note that the design controller based on Sontag formula has an observer and a reference model while the backstepping controller requires only a reference signal. The implementation of an observer in a control system adds complexity but offers advantages in robustness and chattering reduction [69], [70]. Moreover, the backstepping controllers are often combine with an observer [71]. Focusing on the design way and the gain parameters tuning, we note that the proposed controller based on Sontag formula is easier to implement. A part from the three laborious recursive steps that lead to the final backstepping controller, three independent tuning gains (k_1, k_2 and k_3) are generated.

Literature reports some difficulties to tune the backstepping controller gains and some complex solutions may be used to find the best tuning [72], [73], [74], [75], [76]. In addition to the one simple step leading to the construction of the proposed controller based on Sontag formula, there are two gains to tune (λ_0 and λ_1). Unlike the independent gains of the backstepping controller , the gains of the proposed controller depend on each other via the Hurwitz pattern [77].

VI. Simulation Results

In this section, we illustrate the performances of the two controllers obtained while implementing the closed loop control system in Matlab/Simulink environment as it is seen in Fig. 3 and Fig. 4. The simulation lasts 10 seconds and the sampling time is 10 ms. Both constant and sinusoidal reference signals are used. The amplitude of the reference signal is 1 rad/s and the frequency is 2 hz. We choose to vary the viscous damping coefficient of the hydraulic motor as it is often happened in realistic context [78], [79]. Then, the proposed control law based on Sontag formula is compared to the currently used backstepping controller under the hydraulic motor damping disturbances. All the numerical value used for the simulation are listed in Table I.

In order to demonstrate the robustness of the proposed controller, we choose to vary the viscous damping coefficient of the hydraulic motor. Thus, as is shown in the Fig. 5, the initial value of the damping coefficient of the hydraulic motor is 0.2 N.m.s/rad. Between 4s and 6s, the parameter is reduced of 50% of its initial value before returning to 0.2 N.m.s/rad at the end of the simulation.

TABLE I. Numerical values used for the simulation

Symbol	Description	Value and units
	EHSS	
δ_v	Sigmoid function constant $x_2(t)$	10^5
τ	Servovlve time constant	0.01 s
K	Servovalve amplifier gain	$8.10^{-7}m^2/mA$
V_m	Total oil volume of the hydraulic motor	$3\ 10^{-4}m^3$
β	Fluid bulk modulus	$8\ 10^8$ Pa
cd	Flow discharge coefficient	0.61
P_s	Supply pressure	$9\ 10^6$
c_{sm}	Leakage coefficient	$9\ 10^{-13}\ m^5/(N.s)$
d_m	Volumetric displacement of the motor	$3\ 10^{-6}m^3/rad$
ρ	Fluid mass density	$900\ Kg/m^3$
J	Total inertia of the motor and the load	$0.05\ N.m.s^2$
B	Viscous damping coefficient	0.2 N.m.s
	Proposed controller based on Sontag formula	
α_2	Coefficient for the reference model	$2(2\pi \times 20)$
α_1	Coefficient of the reference model	$2(2\pi \times 20)^2$
α_0	Coefficient of the reference model	$(2\pi \times 20)^3$
λ_1	Coefficient for the combined error	$\sqrt{2}(2\pi \times 100)$
λ_0	Coefficient for the combined error	$(2\pi \times 100)^2$
δ_c	Sigmoid function constant for the controller	10^{-6}
	Nonlinear observer	
K_{po}	First column of the gain vector	1143
	backstepping controller	
k_1	Constant of the virtual control 1	106.81
k_2	Constant of the virtual control 2	0.0031
k_3	Constant of the virtual control 3	5 027 000

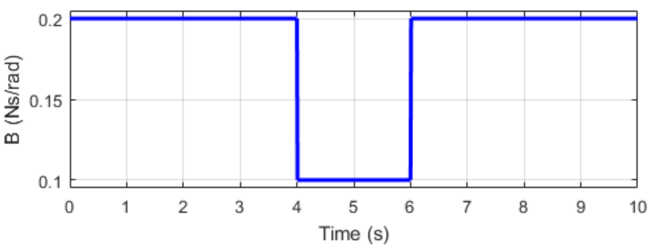

Fig. 5. Simulation of the uncertainty in the viscous damping coefficient

The Fig. 6 and Fig. 7 compare the tracking performances of the proposed controller and the backstepping controller when using a step reference signal with a constant amplitude of 1 rad/s. The backstepping controller shows overshoots reaching 40% and damping oscillations in the starting transient state while the proposed controller shows light overshoot and no visible oscillations. Between 4s and 6s, when the damping torque of the hydraulic motor is reduced, the tracking performance of the backstepping controller slighty deteriorates while the proposed controller maintains zero overshoot.

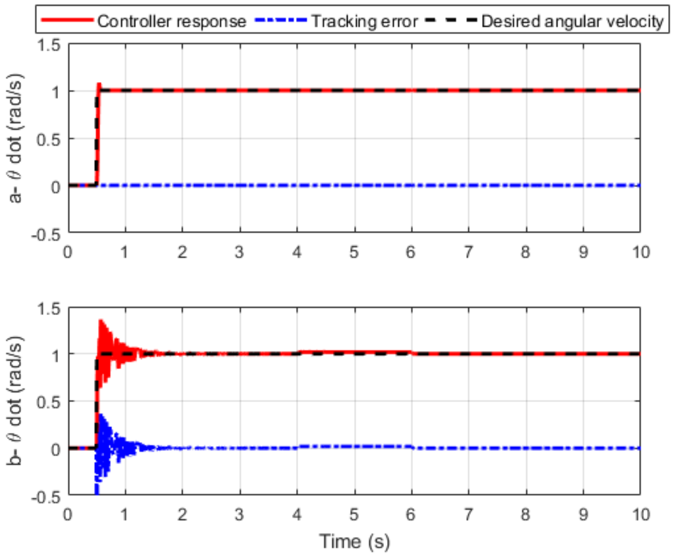

Fig. 6. System response when using (a) the proposed controller (b) the backstepping controller with a step signal reference of 1 rad/s

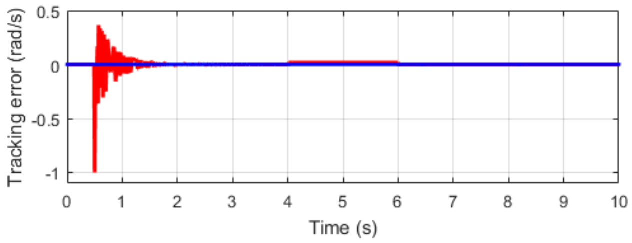

Fig. 7. a- Tracking error of both controllers with a step signal reference of 1 rad/s

In Fig. 8 (b), the control signal of both controllers are compared under the step signal reference of 1 rad/s. The backstepping controller displays large control effort while the proposed controller has small peaks. Moreover, it is shown that the both controllers generate chattering in the control signal. Chattering is due to discontinuities in the controlled systems and fast unmodeled dynamics [80]. In this paper, the sign function is replaced by the continuous sigmoid function to reduce chattering [81]. However, we notice that chattering effects are significant in the backstepping controller while the controller based on Sontag formula presents attenuated chattering effects. The presence of the nonlinear observer in the proposed closed loop controlled system may be the reason of this difference [36]. Other authors indicate that chattering may be caused when the controller gains tuning are not properly done [82]. Our future works will investigate other possibilities to avoid chattering by extending the proposed controller to an adaptive version [83].

The next set of simulation results are obtained when the reference signal is a sinusoidal wave of amplitude 1 rad/s and a frequency of 2Hz. We recall that we extend the design of the controller based on Sontag formula to achieve tracking objectives. Fig. 9 and Fig. 10 show that the proposed controller can track a sine wave very well with a tracking error less than 1%. Between 4s and 6s, when the damping torque is reduced, the proposed controller maintains slight error while the backstepping controller shows a visible tracking error.

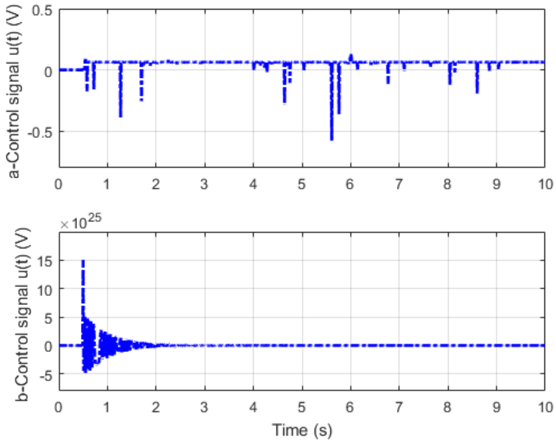

Fig. 8. Control signal of (a) the proposed controller (b) backstepping controller with a zoomed view when using the step reference of amplitude 1 rad/s

Fig. 11 depicts the control signals of both controllers and we see again that chattering is present. We specify that the chattering is no present in the responses but only in the control signals as is also shown in [84] . Chattering is again reduced in the control signal of the proposed control law. Compared to the regulating response, we notice that the variable tracking trajectory clearly reduces the chattering effects. In addition to the chattering effects reduction, the proposed controller shows a smoth control signal while the backstepping control signal generates a strong effort. Moreover, we see in Fig. 11 (b) the presence of a large overshoot at 3.5s while the damping disturbance occurs at 4s. After some observations, we notice that large oscillations are generated when the reference signal sign changes.

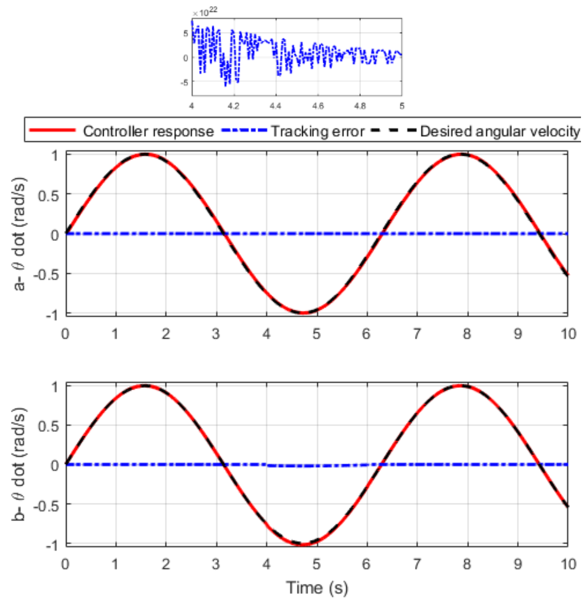

Fig. 9. System response when using (a) the proposed controller (b) the backstepping controller with a sinusoidal signal reference of amplitude 1rad/s and frequency 2hz

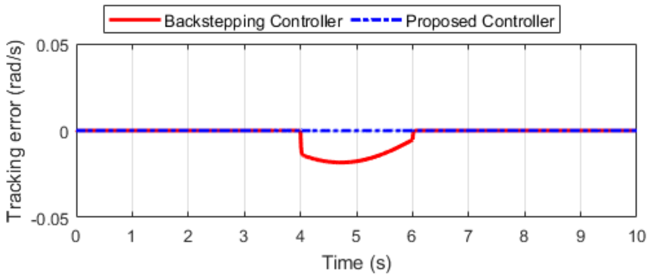

Fig. 10. Tracking error of both controllers with a sinusoidal signal reference of 1rad/s and 2hz

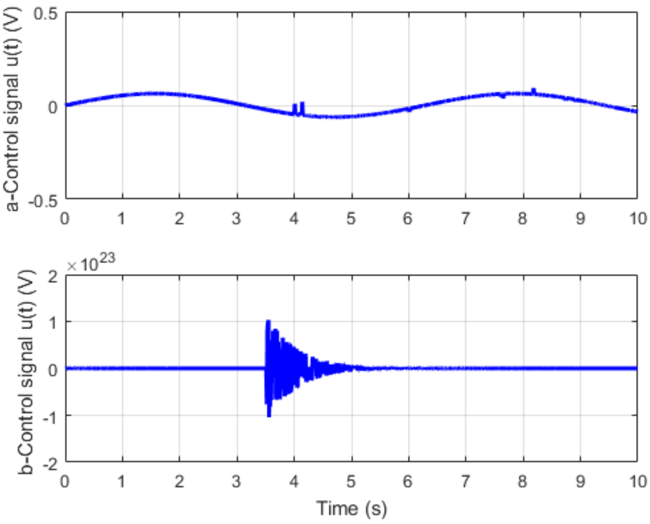

Fig. 11. Control signal of (a) the proposed controller (b) backstepping controller when using a sinusoidal signal reference of 1rad/s amplitude and frequency of 2hz

Finally, Fig.12 shows the behavior of the observation error. We see that the proposed observer track the real output with an observation error smaller than 0.01% for both reference signals. However, when the disturbance occurs, the observation error slightly increases.

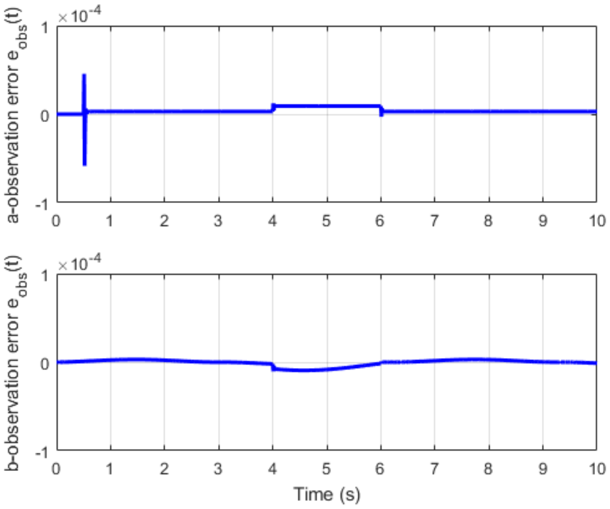

Fig. 12. Observation error when using (a) the constant signal reference and (b) the sinusoidal signal reference

VII. Conclusion

In this paper, we propose an alternative Lyapunov redesign controller to the backstepping one to solve the regulating and the tracking problems of an electrohydraulic velocity drive. The proposed controller is derived from the Sontag formula that the we extend to the tracking version and a nonlinear observer to estimate the derivatives of the output. We found that the proposed control law looks like a sliding mode controller with an equivalent control based on the inverse dynamics. Moreover, the proposed controller generates less design effort and less implementation gain tuning effort than its homologue backstepping. Simulation results show that the proposed control gives better tracking error than the classical backstepping controller for a constant and sinusoidal reference input signal. In addition, under the hydraulic motor damping torque variations, the proposed controller shows the best robust performances.

Future works will involve adaptive or/ and neural version of the proposed controller and an integral action in the nonlinear observer in order to enhance the performance of the controller based on Sontag formula.

References

[1] A. M. Al Aela, J.-P. Kenne, and H. A. Mintsa, "A Novel Adaptive and Nonlinear Electrohydraulic Active Suspension Control System with Zero Dynamic Tire Liftoff," *Machines*, vol. 8, no. 3, p. 38, 2020.

[2] X. Ma, P. K. Wong, and J. Zhao, "Practical multi-objective control for automotive semi-active suspension system with nonlinear hydraulic adjustable damper," *Mechanical Systems and Signal Processing*, vol. 117, pp. 667-688, 2019.

[3] C. Yin, Q. Sun, J. Wu, C. Liu, and J. Gao, "Development of Electrohydraulic Steering Control System for Tractor Automatic Navigation," *Journal of Electrical and Computer Engineering*, vol. 2018, p. 5617253, 2018.

[4] A. Mitov, T. Slavov, J. Kralev, and I. Angelov, "H-infinity Control of an Electrohydraulic Power Steering System," in *2018 41st International Conference on Telecommunications and Signal Processing (TSP)*, pp. 1-4, 2018.

[5] K. Suzumori and A. A. Faudzi, "Trends in hydraulic actuators and components in legged and tough robots: a review," *Advanced Robotics*, vol. 32, no. 9, pp. 458-476, 2018.

[6] J. Mattila, J. Koivumäki, D. G. Caldwell, and C. Semini, "A Survey on Control of Hydraulic Robotic Manipulators With Projection to Future Trends," in *IEEE/ASME Transactions on Mechatronics*, vol. 22, no. 2, pp. 669-680, 2017.

[7] G. Karthik, R. Venkatesh, V. Upender, and N. Kumar, "Design & Analysis of Hydraulic Actuator in a Typical Aerospace Vehicle," *Journal for Research*, vol. 4, no. 02, pp. 7-16, 2018.

[8] Q. Chao, J. Zhang, B. Xu, H. Huang, and M. Pan, "A Review of High-Speed Electro-Hydrostatic Actuator Pumps in Aerospace Applications: Challenges and Solutions," *Journal of Mechanical Design*, vol. 141, no. 5, 2019.

[9] D. Xu, Z. Feng, S. Sui, and Y. H. Lin, "Reliability Assessment of Electrohydraulic Actuation Control System Subject to Multisources Degradation Processes," *IEEE/ASME Transactions on Mechatronics*, vol. 24, no. 6, pp. 2594-2605, 2019.

[10] G. N. Sahu, S. Singh, A. Singh, and M. Law, "Static and Dynamic Characterization and Control of a High-Performance Electro-Hydraulic Actuator," *Actuators*, vol. 9, no. 2, p. 46, 2020.

[11] S. Li *et al.*, "Failure analysis for hydraulic system of heavy-duty machine tool with incomplete failure data," *Applied Sciences*, vol. 11, no. 3, p. 1249, 2021.

[12] Z. Liang-kuan, W. Zi-bo, and L. Ya-qiu, "Compound Control Strategy for MDF Continuous Hot Pressing Electrohydraulic Servo System with Uncertainties and Input Saturation," *Mathematical Problems in Engineering*, vol. 2016, p. 3936810, 2016.

[13] H. Zhang, L. Ren, Y. Gao, and B. Jin, "A Comprehensive Study of Energy Conservation in Electric-Hydraulic Injection-Molding Equipment," *Energies*, vol. 10, no. 11, p. 1768, 2017.

[14] R. P. Borase, D. K. Maghade, S. Y. Sondkar, and S. N. Pawar, "A review of PID control, tuning methods and applications," *International Journal of Dynamics and Control*, vol. 9, no. 2, pp. 818-827, 2021.

[15] H. E. Merritt, Hydraulic Control Systems. Wiley, 1967.

[16] P. Tamburrano, A. R. Plummer, E. Distaso, and R. Amirante, "A review of electro-hydraulic servovalve research and development," *International Journal of Fluid Power*, pp. 1-23, 2018.

[17] C. Soon, R. Ghazali, H. Jaafar, S. Hussien, Y. Sam, and M. Rahmat, "The effects of parameter variation in open-loop and closed-loop control scheme for an electro-hydraulic actuator system," *International Journal of Control and Automation*, vol. 9, no. 11, pp. 283-294, 2016.

[18] H. Feng, W. Ma, C. Yin, and D. Cao, "Trajectory control of electro-hydraulic position servo system using improved PSO-PID controller," *Automation in Construction*, vol. 127, p. 103722, 2021.

[19] Y. Fan, J. Shao, and G. Sun, "Optimized PID Controller Based on Beetle Antennae Search Algorithm for Electro-Hydraulic Position Servo Control System," *Sensors*, vol. 19, no. 12, p. 2727, 2019.

[20] T. Van Nguyen and C. Ha, "Experimental study of sensor fault-tolerant control for an electro-hydraulic actuator based on a robust nonlinear observer," *Energies*, vol. 12, no. 22, p. 4337, 2019.

[21] N. Ishak *et al.*, "PID Studies on Position Tracking Control of an Electro-Hydraulic Actuator," *International Journal of Control Science and Engineering*, vol. 2, pp. 120-126, 2012.

[22] G. Wrat, M. Bhola, P. Ranjan, S. K. Mishra, and J. Das, "Energy saving and Fuzzy-PID position control of electro-hydraulic system by leakage compensation through proportional flow control valve," *ISA Transactions*, vol. 101, pp. 269-280, 2020.

[23] T. Samakwong and W. Assawinchaichote, "PID Controller Design for Electro-hydraulic Servo Valve System with Genetic Algorithm," *Procedia Computer Science*, vol. 86, pp. 91-94, 2016.

[24] X. Sun, N. Liu, R. Shen, K. Wang, Z. Zhao, and X. Sheng, "Nonlinear PID Controller Parameters Optimization Using Improved Particle Swarm Optimization Algorithm for the CNC System," *Applied Sciences*, vol. 12, no. 20, p. 10269, 2022.

[25] O. A. Somefun, K. Akingbade, and F. Dahunsi, "The dilemma of PID tuning," *Annual Reviews in Control*, vol. 52, pp. 65-74, 2021.

[26] M. Krstic, A. P. V. Kokotovic, and A. I. Kanellakopoulos, Nonlinear and Adaptive Control Design. John Wiley & Sons, Inc., 1995.

[27] Z. Artstein, "Stabilization with relaxed controls," *Nonlinear Analysis-theory Methods & Applications*, vol. 7, no. 11, pp. 1163-1173, 1983.

[28] E. D. Sontag, "A 'universal' construction of Artstein's theorem on nonlinear stabilization," *Systems & Control Letters*, vol. 13, no. 2, pp. 117-123, 1989.

[29] D. X. Ba, K. K. Ahn, D. Q. Truong, and H. G. Park, "Integrated model-based backstepping control for an electro-hydraulic system," *International Journal of Precision Engineering and Manufacturing*, vol. 17, no. 5, pp. 565-577, 2016.

[30] C. Kaddissi, M. Saad, and J.-P. Kenné, "Interlaced Backstepping and Integrator Forwarding for Nonlinear Control of an Electrohydraulic Active Suspension," *Journal of Vibration and Control*, vol. 15, no. 1, pp. 101-131, 2009.

[31] L. Li, Y. Jiang, X. Yang, and J. Yao, "Rapid-Erection Backstepping Tracking Control for Electrohydraulic Lifting Mechanisms of Launcher Systems," *Applied Sciences*, vol. 12, no. 2, p. 893, 2022.

[32] H. M. Kim, S. H. Park, J. H. Song, and J. S. Kim, "Robust Position Control of Electro-Hydraulic Actuator Systems Using the Adaptive Back-Stepping Control Scheme," *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, vol. 224, no. 6, pp. 737-746, 2010.

[33] X. Ji, C. Wang, Z. Zhang, S. Chen, and X. Guo, "Nonlinear adaptive position control of hydraulic servo system based on sliding mode back-stepping design method," *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, vol. 235, no. 4, pp. 474-485, 2021.

[34] Z. Wan, L. Yue, and Y. Fu, "Neural Network Based Adaptive Backstepping Control for Electro-Hydraulic Servo System Position Tracking," *International Journal of Aerospace Engineering*, vol. 2022, 2022.

[35] A. M. Al Aela, J.-P. Kenne, and H. A. Mintsa, "Adaptive neural network and nonlinear electrohydraulic active suspension control system," *Journal of Vibration and Control*, vol. 28, no. 3-4, pp. 243-259, 2022.

[36] Y. Chen, Q. Zhang, Q. Tian, and X. Feng, "Extended State Observer-Based Fuzzy Adaptive Backstepping Force Control of a Deep-Sea Hydraulic Manipulator with Long Transmission Pipelines," *Journal of Marine Science and Engineering*, vol. 10, no. 10, p. 1467, 2022.

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

[38] I. Karafyllis and Z.-P. Jiang, Stability and stabilization of nonlinear systems. Springer Science & Business Media, 2011.

[39] Y. Kim and J. M. Lee, "Model-based reinforcement learning for nonlinear optimal control with practical asymptotic stability guarantees," *AIChE Journal*, vol. 66, no. 10, p. e16544, 2020.

[40] B. Lohmann and J. Bongard, "A Discussion on Nonlinear Quadratic Control and Sontag's Formula," arXiv preprint arXiv:2301.10594, 2023.

[41] N. Marchand, S. Durand, and J. F. G. Castellanos, "A General Formula for Event-Based Stabilization of Nonlinear Systems," in *IEEE Transactions on Automatic Control*, vol. 58, no. 5, pp. 1332-1337, 2013.

[42] J. Acosta, A. Dòria-Cerezo, and E. Fossas, "Stabilisation of state-and-input constrained nonlinear systems via diffeomorphisms: A Sontag's formula approach with an actual application," *International Journal of Robust and Nonlinear Control*, vol. 28, no. 13, pp. 4032-4044, 2018.

[43] M. Ekramian, S. Hosseinnia, and F. Sheikholeslam, "General framework in designing Luenberger-like non-linear observer," *IET Control Theory & Applications*, vol. 7, no. 2, pp. 253-260, 2013.

[44] C. Kaddissi, J. P. Kenne, and M. Saad, "Identification and Real-Time Control of an Electrohydraulic Servo System Based on Nonlinear Backstepping," *IEEE/ASME Transactions on Mechatronics*, vol. 12, no. 1, pp. 12-22, 2007.

[45] M. Jelali and A. Kroll, Hydraulic servo-systems: modelling, identification and control. Springer Science & Business Media, 2002.

[46] V. D. Yurkevich, Design of nonlinear control systems with the highest derivative in feedback. World Scientific, 2004.

[47] J. Seo, R. Venugopal, and J.-P. Kenné, "Feedback linearization based control of a rotational hydraulic drive," *IFAC Proceedings Volumes*, vol. 40, no. 12, pp. 940-945, 2007.

[48] H. Angue-Mintsa, R. Venugopal, J.-P. Kenné, and C. Belleau, "Adaptive Position Control of an Electrohydraulic Servo System With Load Disturbance Rejection and Friction Compensation," *Journal of Dynamic Systems, Measurement, and Control*, vol. 133, no. 6, 2011.

[49] M. Honorine Angue, V. Ravinder, K. Jean-Pierre, and B. Christian, "Feedback Linearization-Based Position Control of an Electrohydraulic Servo System With Supply Pressure Uncertainty," *IEEE Transactions on Control Systems Technology*, vol. 20, no. 4, pp. 1092-1099, 2012.

[50] M. F. Ghani, R. Ghazali, H. I. Jaafar, C. C. Soon, Y. M. Sam, and Z. Has, "Improved Third Order PID Sliding Mode Controller for Electrohydraulic Actuator Tracking Control," *Journal of Robotics and Control (JRC)*, vol. 3, no. 2, pp. 219-226, 2022.

[51] S. Lin, G. An, J. Huang, and Y. Guo, "Robust Backstepping Control with Active Damping Strategy for Separating-Metering Electro-Hydraulic System," *Applied Sciences*, vol. 10, no. 1, p. 277, 2020.

[52] J. Seo, R. Venugopal, and J.-P. Kenné, "Feedback linearization based control of a rotational hydraulic drive," *Control Engineering Practice*, vol. 15, no. 12, pp. 1495-1507, 2007.

[53] R. Spencer, "Applying the Electro-Hydraulic Servo Valve to Industry," *IRE Transactions on Industrial Electronics*, vol. PGIE-7, pp. 33-39, 1958.

[54] Y. He, J. Wang, and R. Hao, "Adaptive robust dead-zone compensation control of electro-hydraulic servo systems with load disturbance rejection," *Journal of Systems Science and Complexity*, vol. 28, no. 2, pp. 341-359, 2015.

[55] S. Sastry, Nonlinear systems: analysis, stability, and control. Springer Science & Business Media, 2013.

[56] W. M. Haddad and V. Chellaboina, "Nonlinear dynamical systems and control," in Nonlinear Dynamical Systems and Control: Princeton university press, 2011.

[57] J.-J. E. Slotine, Applied nonlinear control / Jean-Jacques E. Slotine,... Weiping Li. Englewood Cliffs (N.J.): Prentice Hall, 1991.

[58] M. D. Stefano, H. Mishra, R. Balachandran, R. Lampariello, C. Ott, and C. Secchi, "Multi-Rate Tracking Control for a Space Robot on a Controlled Satellite: A Passivity-Based Strategy," *IEEE Robotics and Automation Letters*, vol. 4, no. 2, pp. 1319-1326, 2019.

[59] Y. Shtessel, C. Edwards, L. Fridman, and A. Levant, Sliding mode control and observation. Springer, 2014.

[60] W. Perruquetti and J. P. Barbot, Sliding mode control in engineering. Marcel Dekker New York, 2002.

[61] W. Zhang, H. Su, F. Zhu, and S. Bhattacharyya, "Improved exponential observer design for one-sided Lipschitz nonlinear systems," *International Journal of Robust and Nonlinear Control*, vol. 26, pp. 3958-3973, 2016.

[62] G. Chen *et al.*, "Research on Feedback-Linearized Sliding Mode Control of Direct-Drive Volume Control Electro-Hydraulic Servo System," *Processes*, vol. 9, no. 9, p. 1676, 2021.

[63] K. Wróbel, K. Śleszycki, K. Szabat, and S. Katsura, "Application of Multilayer Observer for a Drive System with Flexibility," *Energies*, vol. 14, no. 24, p. 8479, 2021.

[64] M. A. Márquez-Vera, A. Rodríguez-Romero, C. A. Márquez-Vera, K. R. R. Ramos-Téllez, "Interval Type-2 Fuzzy Observers Applied in Biodegradation," *International Journal of Robotics and Control Systems*, vol. 1, no. 2, pp. 145-158, 2021.

[65] 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.

[66] L. Zhou, J. Zhang, H. She, and H. Jin, "Quadrotor UAV flight control via a novel saturation integral backstepping controller," *Journal for Control, Measurement, Electronics, Computing and Communications*, vol. 60, no. 2, pp. 193-206, 2019.

[67] X. Xu, K. Watanabe, I. Nagai, "Backstepping control for a tandem rotor UAV Robot with two 2-DOF tiltable coaxial rotors," *Journal of Robotics and Control (JRC)*, vol. 2, no. 5, pp. 413-420, 2021.

[68] A. Ma'arif, M. A. M. Vera, M. S. Mahmoud, S. Ladaci, A. Çakan, and J. N. Parada, "Backstepping sliding mode control for inverted pendulum system with disturbance and parameter uncertainty," *Journal of Robotics and Control (JRC)*, vol. 3, no. 1, pp. 86-92, 2022.

[69] S. Zeghlache and N. Amardjia, "Real time implementation of non linear observer-based fuzzy sliding mode controller for a twin rotor multi-input multi-output system (TRMS)," *Optik*, vol. 156, pp. 391-407, 2018.

[70] E. Sariyildiz and K. Ohnishi, "A Guide to Design Disturbance Observer," *Journal of Dynamic Systems, Measurement, and Control*, vol. 136, no. 2, 2013.

[71] M. Khamar and M. Edrisi, "Designing a backstepping sliding mode controller for an assistant human knee exoskeleton based on nonlinear disturbance observer," *Mechatronics*, vol. 54, pp. 121-132, 2018.

[72] Z. Wang, X. Liu, and W. Wang, "Linear-based gain-determining method for adaptive backstepping controller," *ISA Transactions*, vol. 127, pp. 342-349, 2022.

[73] J. -X. Zhang, Q. -G. Wang, and W. Ding, "Global Output-Feedback Prescribed Performance Control of Nonlinear Systems With Unknown Virtual Control Coefficients," in *IEEE Transactions on Automatic Control*, vol. 67, no. 12, pp. 6904-6911, 2022.

[74] O. Rodríguez-Abreo, J. M. Garcia-Guendulain, R. Hernández-Alvarado, A. F. Rangel, and C. Fuentes-Silva, "Genetic Algorithm-Based Tuning of Backstepping Controller for a Quadrotor-Type Unmanned Aerial Vehicle," *Electronics*, vol. 9, no. 10, p. 1735, 2020.

[75] O. Rodríguez-Abreo, F.-J. Ornelas-Rodríguez, A. Ramírez-Pedraza, J. B. Hurtado-Ramos, and J.-J. González-Barbosa, "Backstepping control for a UAV-manipulator tuned by Cuckoo Search algorithm," *Robotics and Autonomous Systems*, vol. 147, p. 103910, 2022.

[76] C. Li, Y. Zhang, and P. Li, "Full control of a quadrotor using parameter-scheduled backstepping method: implementation and experimental tests," *Nonlinear Dynamics*, vol. 89, no. 2, pp. 1259-1278, 2017.

[77] J. C. Escobar, R. Lozano, and M. Bonilla Estrada, "PVTOL control using feedback linearisation with dynamic extension," *International Journal of Control*, vol. 94, no. 7, pp. 1794-1803, 2021.

[78] M. Cheng, B. Xu, J. Zhang, and R. Ding, "Pump-based compensation for dynamic improvement of the electrohydraulic flow matching system," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 4, pp. 2903-2913, 2016.

[79] M. Cheng, J. Zhang, B. Xu, R. Ding and J. Wei, "Decoupling Compensation for Damping Improvement of the Electrohydraulic Control System With Multiple Actuators," in *IEEE/ASME Transactions on Mechatronics*, vol. 23, no. 3, pp. 1383-1392, 2018.

[80] V. Utkin and L. Hoon, "Chattering Problem in Sliding Mode Control Systems," in International Workshop on Variable Structure Systems, 2006. VSS'06., 2006, pp. 346-350.

[81] N. Ren, L. Fan, and Z. Zhang, "Sensorless PMSM control with sliding mode observer based on sigmoid function," *Journal of Electrical Engineering & Technology*, vol. 16, no. 2, pp. 933-939, 2021.

[82] M. S. Mahmoud, A. Alameer, and M. M. Hamdan, "An adaptive sliding mode control for single machine infinite bus system under unknown uncertainties," *International Journal of Robotics and Control Systems*, vol. 1, no. 3, pp. 226-243, 2021.

[83] C. Sun, X. Dong, M. Wang, and J. Li, "Sliding Mode Control of Electro-Hydraulic Position Servo System Based on Adaptive Reaching Law," *Applied Sciences*, vol. 12, no. 14, p. 6897, 2022.

[84] A. Ma'arif, M. A. M. Vera, M. S. Mahmoud, E. Umoh, A. J. Abougarair, and S. N. Rahmadhia, "Sliding Mode Control Design for Magnetic Levitation System," *Journal of Robotics and Control (JRC)*, vol. 3, no. 6, pp. 848-853, 2022.