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ANALYSIS OF FUZZY COMPENSATION APPLIED ON THE CONTROL OF ELECTRO-HYDRAULIC SERVO SYSTEMS

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Abstract. *Electro-hydraulic actuators are widely used in applications that require high power to size ratio, as well as high force and torque. They stand out for their quick response time when compared to electrical and non-hydraulic systems. However, this system has a high degree of nonlinearity present in its dynamics, such as the dead zone - which degrades the performance of the controlled system and generates instability in the closed loop system. Controllers based on conventional linear techniques have their performance compromised when facing such phenomena, therefore its needed the use of efficient techniques capable of guaranteeing the performance. The application of non-linear control techniques in the design of controllers, such as feedback linearization and, sliding modes, along with compensations based on artificial intelligence technique as fuzzy logic and neural networks shows excellent results. Previous publications demonstrate the robustness and performance of controllers using these techniques with compensations against uncertainties, proving their efficiency. This research seeks to compare the performance of the fuzzy compensator when configured with triangular membership functions, which are equally spaced or spaced in a heuristic way. Results obtained from numerical simulations demonstrate the differences between each compensation strategy, as well as the efficiency and stability of the controller.*

Keywords: *fuzzy logic, feedback linearization, sliding modes, nonlinear control*

1. INTRODUCTION

The study of nonlinear control techniques has driven great interest among engineers and researchers due to their potential for improving the control of robotic systems and biomedical procedures. These techniques are capable of operating in unknown and large operational ranges, with parameters that are not perfectly known by the controller. This is an advantage compared to linear control, which exhibits performance loss when faced with uncertainties.

A significant number of mechanical systems in engineering exhibits nonlinear characteristics in their modeling. This aspect can be effectively addressed through the implementation of nonlinear control techniques, allowing for better treatment of the equations and improved performance of the control variable.

The strategies that can be applied for the construction of nonlinear controllers are: linearization control, adaptive control, feedback linearization, sliding mode control, direct Lyapunov method, backstepping, and so on.

Among numerous systems in the field of engineering, electro-hydraulic actuator systems have been widely used in the industrial sector in recent years. They are capable of operating in robust systems that require high loads and high speeds. As a result, these actuators can maintain a fast response signal, unlike systems with solely electric actuators, which not only have limited actuation force capacity but also consume a significant amount of electrical energy and generate excess heat (Jovanovic *et al.*, 2016).

Despite their advantages, this type of system exhibits highly nonlinear behavior in its dynamics, which is inherent to fluid compression and flow valve properties. This complexity blocks the application of conventional linear control methods for its operation. Several studies aim to optimize the efficiency of these systems by combining nonlinear control techniques, such as sliding mode control with backstepping or feedback lineatization (Zang *et al.*, 2022; Chen *et al.*, 2021). Some papers also utilize neural networks to make the controller overcome difficulties when in front of unknown parameters (Feng *et al.*, 2022; Yang and Yao, 2022; Guo and Chen, 2021). Adaptative neuro-fuzzy for the guarantee of the tracking is also present (Yu *et al.*, 2021).

In addition to the nonlinear dynamics, electro-hydraulic actuators are also subject to the effects of a significant dead zone, which occurs when the valve spool overlaps the fluid passage orifice, impeding flow and generating system instability and controller degradation (Bessa, 2022).

In order to minimize the effects of the dead zone, several studies have developed more robust and adaptive control strategies to prevent controller degradation (Yang and Tong, 2016; Zhou *et al.*, 2017) or a characteristic model for predictive control (Liu *et al.*, 2018). Among proposed improvements, the addition of an inverse function to compensate for nonlinearity has been highlighted. However, these functions are discontinuous and can lead to input signal switching and trajectory loss, or the addition of a combination of a linear function and a saturation function to the control law, that can be integrated with optimization techniques (Changyong *et al.*, 2020).

In this study, nonlinear control laws based on feedback linearization and sliding mode techniques are presented, with compensation based on fuzzy logic. Different applications of fuzzy logic membership functions are employed to assess the efficiency of the controller.

2. FEEDBACK LINEARIZATION

The feedback linearization (FL) technique involves implementing a control law in a nonlinear system that transforms the closed-loop dynamics of the system into a linear one. It is the transformation of a dynamic system into an equivalent one that cancels the nonlinearities present in its modeling (Slotine and Li, 1991).

The simple linear dynamics that cancel the nonlinearities of the system can be obtained in a generic manner from a nonlinear and non-autonomous dynamic system, as shown in Eq. (1).

$$\begin{cases} x^n = f(x,t) + b(x,t)u(t) \\ y = x \end{cases} \tag{1}$$

where $\mathbf{x} = [x_1 + x_2 + \cdots + x_n] = [x, \dot{x}, \ddot{x}, \cdots, x^{(n-1)}] = [x, x^{(1)}, x^{(2)}, \cdots, x^{(n-1)}]$ is the vector of state variables, x^n represents the n-th derivative of the state variable x, and u and y are input variables of the system. The functions f, $b : \mathbf{R}^n \to \mathbf{R}$ are nonlinear and time-varying.

The trajectory tracking problem is defined as $x_d = [x, \dot{x}, \ddot{x}, \cdots, x^{(n-1)}]$, where the controller aims to make $\mathbf{x} \to \mathbf{x}_d$ as $t \to \infty$, meaning that $\tilde{\mathbf{x}} \to \mathbf{x} - \mathbf{x}_d = [\tilde{x}, \dot{\tilde{x}}, \cdots, \tilde{x}^{(n-1)}]$ defined as the tracking error. Based on this, with the state vector $\mathbf{x}$ available for measurement, the fully defined functions f and b, and $b(x,t)$ not equal to zero, the control law can be represented as follows:

$$u = b^{-1}(-f + x_d^{(n)} - k_0\tilde{x} - k_1\dot{\tilde{x}} - \cdots - k_{n-1}\tilde{x}^{(n-1)}) \tag{2}$$

where the guarantee that $\tilde{x} \to 0$ as $t \to \infty$ is possible if the coefficients $k = [k_0, k_1, \cdots, k_{n-1}]$ make the polynomial $p^n + k_{(n-1)}p^{(n-1)} + \cdots + k_0$ a Hurwitz polynomial.

Therefor, a Hurwitz polynomial is defined as a polynomial which coefficients are positive real numbers and whose roots are located in the left region of the complex plane, meaning that the real part of each root is negative.

By substituting Eq. (2) into the dynamic system of Eq. (1), a closed-loop system is obtained, with dynamics exhibiting stable behavior and exponential convergence to zero over time, associated with a Hurwitz polynomial, as indicated below:

$$\tilde{x}^{(n)} + k_{n-1}\tilde{x}^{(n-1)} + \cdots + k_1\dot{\tilde{x}} + k_0\tilde{x} = 0 \tag{3}$$

An example of a second-order, Eq. (3) is defined as $\ddot{\tilde{x}} + k_1\dot{\tilde{x}} + k_0\tilde{x} = 0$. It can be observed that if the associated polynomial is a Hurwitz polynomial, the dynamic system exhibits stable behavior and converges exponentially to zero.

Despite its simplicity and application in various fields, this type of control only operates effectively when all the system parameters are known. In the presence of uncertainties, the controller significantly loses its performance. To address these losses, artificial intelligence techniques are incorporated into the system's control laws, as will be shown in this study.

3. SLIDING MODES

The sliding mode control (SMC) technique is used in problems which there are parametric uncertainties or when the complete dynamics is unknown during operation. It is based on defining sliding surfaces in terms of the tracking errors of the states found in the system.

The methodology of this technique involves reduction of the nonlinear control problem from n equations to a first-order system. Thus, the control law developed in sliding modes causes the system trajectories to converge to a surface $s(x,t) = 0$ within a finite time interval, and once reached, the system "slides" exponentially along the surface until reaching x_d. This surface is called a sliding surface or sliding mode.

Therefore, the system states are forced by the controller to converge to the sliding surface, and upon reaching it, the system error converges to zero. The $\mathbf{s(t)}$ for an n-order dynamic system is defined by Eq. (4):

$$s(\mathbf{x},t) = (\frac{d}{dt} + \lambda)^{n-1}\tilde{x} = \mathbf{\Lambda}^T\tilde{\mathbf{x}} \tag{4}$$

Here, λ is a positive constant, calculated by $\mathbf{\Lambda} = [c_{n-1}\lambda^{n-1}, c_{n-2}\lambda^{n-2}, \cdots, c_1\lambda, c_0]$.

In order to ensure the permanence of states on the sliding surface in the presence of disturbances and uncertainties in the system, a discontinuous term is added to compensate for these uncertainties. This results in the control law indicated by the equation below:

$$u = b^{-1}(-\hat{f} + x_d^{(n)} - \Lambda_u^T - Ksgn(s)) \tag{5}$$

In the above equation, K is the robustness factor associated with the added discontinuous term, Λ_u is part of the Hurwitz polynomial, which guarantees that the dynamic system becomes stable and its exponential convergence tends to zero. $\Lambda_u = [0, \lambda^{n-1}, c_{n-1}\lambda^{n-2}, \cdots, c_2\lambda]$, and $sgn(s)$ is defined as:

$$sgn(s) = \begin{cases} -1 & \text{if } s < 0 \\ 0 & \text{if } s = 0 \\ 1 & \text{if } s > 0 \end{cases} \tag{6}$$

When using the sign function and adding disturbances to the system, excessive oscillations of the manipulated variable u occur. This phenomenon, known as chattering, often leads to structural vibrations in the equipment.

One solution to this phenomenon, proposed by Slotine and Li (1991), is to add a boundary layer ϕ to the boundaries of the sliding surface, causing the control law to converge more smoothly. To apply the boundary layer, the discontinuous function $sgn(s)$ is replaced by a saturation function defined as follows:

$$sat(\frac{s}{\phi}) = \begin{cases} sgn(s) & \text{if } \left|\frac{s}{\phi}\right| \geq 1 \\ \frac{s}{\phi} & \text{if } \left|\frac{s}{\phi}\right| < 1 \end{cases} \tag{7}$$

Therefore, the control law can be declared as:

$$u = b^{-1}(-\hat{f} + x_d^{(n)} - \Lambda_u^T - Ksat\frac{s}{\phi}) \tag{8}$$

Chattering is minimized or completely eliminated, but the convergence of this error is confined to a layer close to zero, resulting in performance loss in the controller's trajectory.

4. FUZZY COMPENSATIONS

Fuzzy compensation arises to ensure the desired trajectory of the controller when its performance is affected by uncertainties in the dynamic system or limitations of the control technique. Thus, in the control laws proposed in this work, a term d is added. When incorporated into the equation, this term is responsible for compensating the mathematical model and ensuring trajectory tracking.

The proposed control law using the feedback linearization technique can be found in Eq. (9).

$$u = b^{-1}(-f + x_d^{(n)} - k_0\tilde{x} - k_1\dot{\tilde{x}} - \cdots - k_{n-1}\tilde{x}^{(n-1)}) + d_r(\tilde{\mathbf{x}}) \tag{9}$$

The structure of the control system for this case can be visualized in the block diagram shown in Fig. (1).

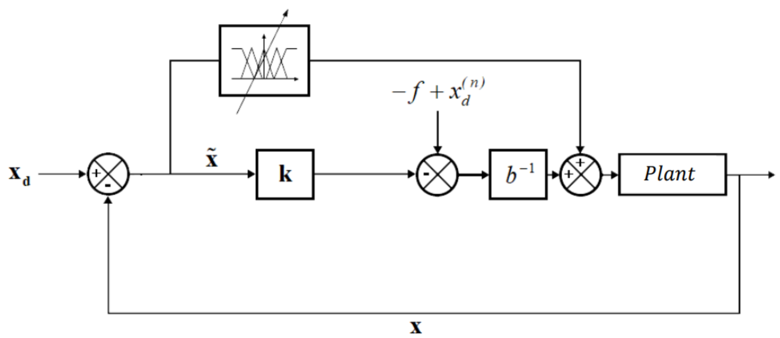

Figure 1. Block diagram of the controller using feedback linearization with fuzzy compensation.

For the sliding mode-based controller, the compensation performed by fuzzy logic will bypass the boundary layer formed by the addition of the saturation function. This function will be responsible for defining the fuzzy input sets that, with the proper manipulation of the output parameters, has the ability to correct system imperfections. Equation (10) describes the control law for sliding modes with fuzzy compensation.

$$u = b^{-1}(-\hat{f} + x_d^{(n)} - \Lambda_u^T - Ksat\frac{s}{\phi} + d_r(\tilde{\mathbf{x}})) \tag{10}$$

The structure of the control system can be visualized in the block diagram shown in Fig. (2).

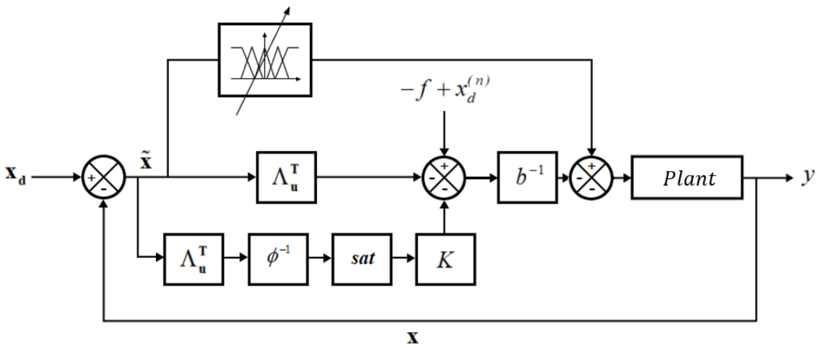

Figure 2. Block diagram of the controller using sliding modes with fuzzy compensation.

It is worth mentioning the importance of membership functions for the controller design, as they represent the possibility of events occurring simultaneously and contain the necessary logic for decision-making in different situations. The membership functions can be of the Gaussian, triangular, or trapezoidal type. In this work, triangular membership functions were used.

The compensator d_r was calculated using the TSK (Takagi-Sugeno-Kang) fuzzy inference system, of zero order, with the rule r_n, determined as follows:

If $\tilde{x}$ is $\tilde{X}_r$ and $\dot{\tilde{X}}_r, \cdots$ and $\tilde{x}^{(n-1)}$ is $\dot{\tilde{X}}_r^{(n-1)}$, so $d_r = D_r$ where $r = 1, 2, \cdots$, N where $\tilde{\mathbf{X}}_\mathbf{r}$, $\dot{\tilde{\mathbf{X}}}_\mathbf{r}$, and $\dot{\tilde{\mathbf{X}}}_\mathbf{r}^{(\mathbf{n-1})}$ are fuzzy sets, and their membership functions can be chosen in a way that best suits the system. D_r is the output value for each of the N fuzzy rules. The final output value d_r can be calculated by a weighted average Eq. (11).

$$d_r(\tilde{\mathbf{x}}) = \frac{\sum_{r=1}^{N} w_r D_r}{\sum_{r=1}^{N} w_r} \tag{11}$$

5. ELECTRO-HYDRAULIC SYSTEM

The electro-hydraulic system consists of a four-way proportional valve, where P_s is the supply pressure and P_0 is the pressure that returns to the reservoir, and a hydraulic cylinder subjected to variable dynamic loading, as depicted in Fig. (3). The dynamic model of the electro-hydraulic system is well established in the specialized literature (Merritt, 1967).

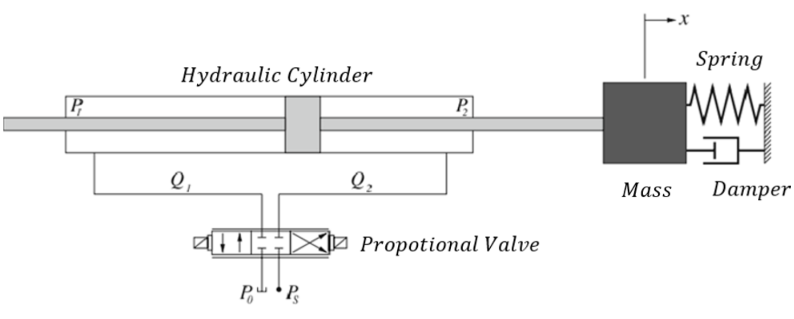

Figure 3. Schematics of an electro-hydraulic system.

The dynamics of the electro-hydraulic system can be found in the literature and is shown in Eq. (12).

$$F_g = A_1 P_1 - A_2 P_2 = M_t \ddot{x} + B_t \dot{x} + K_s x \tag{12}$$

where F_g is the force generated by the piston, P_1 and P_2 are the pressures acting on the cylinder, A_1 and A_2 are the piston areas, M_t is the total mass of the piston and load, B_t is the viscous friction coefficient of the system, K_s is the spring constant, and $\mathbf{x}$ represents the piston displacement.

By combining continuity, leakage, discharge equations, and considering dead-zone parameters, a third-order differential equation representing the dynamic behavior of the electro-hydraulic system is obtained:

$$\dddot{x} = -a^T x + bu - bd \tag{13}$$

where $x = [x, \dot{x}, \ddot{x}]$ is the state vector with an associated coefficient vector $a = [a_0, a_1, a_2]$, defined as:

$$a_0 = \frac{4\beta_e C_{tp} K_s}{V_t M_t} \tag{14}$$

$$a_1 = \frac{K_s}{M_t} + \frac{4\beta_e A_p^2}{V_t M_t} + \frac{4\beta_e C_{tp} K_s}{V_t M_t} \tag{15}$$

$$a_2 = \frac{K_s}{M_t} + \frac{4\beta_e C_{tp}}{V_t} \tag{16}$$

The controller gain is defined as:

$$b = \frac{4\beta_e A_p}{V_t M_t} C_d w k_v \sqrt{\frac{1}{\rho}[P_s - \text{sgn}(u)(M_t \ddot{x} + B_t \dot{x} + K_s x)/A_p]} \tag{17}$$

6. RESULTS AND DISCUSSION

The controller's performance was evaluated through numerical computational implementation in the C language, with a sampling rate of 500 Hz for the controller and 1 kHz for the simulator. The third-order equation of the dynamic modeling of the actuator was converted into a system of three first-order equations and solved using the fourth-order Runge-Kutta numerical method. The parameters adopted for the system were: M_t = 250 kg, V_t = $6x10^{-5}$ m³, A_p = $3x10^{-4}$ m², K_s = 75 N/m, B_t = 100 Ns/m, β_e = $7x10^8$ Pa, C_{tp} = $2x10^{-12}$ m²/sPa, C_d = 0.6, w = $2.5x10^{-2}$ m, ρ = 850 kg/m, and P_s = $7x10^6$ Pa. The controller parameter λ was set as λ = 6, and the desired trajectory x_d was defined as x_d = $0.5\sin(0.1t)$.

The differential in the analysis was the use of triangular membership functions (MF) defined in such a way that their values could be equally or heuristically spaced for each controller based on feedback linearization and sliding modes.

6.1 Control using feedback linearization

Considering a real system where there are measurement uncertainties originating from pressure sensors, hysteresis, effects of the working fluid, temporal conditions. In addition, due to the difficulty of maintaining constant pressure at the system's output, which is intrinsic to hydraulic units, a supply pressure P_s = 7 MPa with a fluctuation of $\pm 12\%$ relative to the estimated value was adopted. The actuator was limited to a voltage of 6V.

Since the parameters δ_1, δ_2 and the dynamics of the model are not known, the feedback linearization (FL) control law is not able to guarantee the convergence of the trajectory error to zero, confirming the limitations of the technique in the face of modeling uncertainties, as indicated in Fig. (4).

To compensate for this performance loss of the controller, fuzzy logic compensation is added to the control law. Fuzzy inputs where sets were defined in the error phase space, which, based on the parameters added to the system, provide corrections to the controller's operation.

The central values for the equally spaced case was spaced as follows:

- $C_e = \{0.12; -0.8; -0.4; 0; 0.4; 0.8; 0.12\}$ for the error.
- $C_{de} = \{-0.03; -0.02; -0.01; 0; 0.01; 0.02; 0.03\}$ for the error derivative.

For the heuristically spaced set, it was defined as:

- $C_e = \{-0.12; -0.024; -0.0024; 0; 0.0024; 0.024; 0.12\}$ for the error.
- $C_{de} = \{-0.03; -0.015; -0.006; 0; 0.006; 0.015; 0.0\}$ for the error derivative.

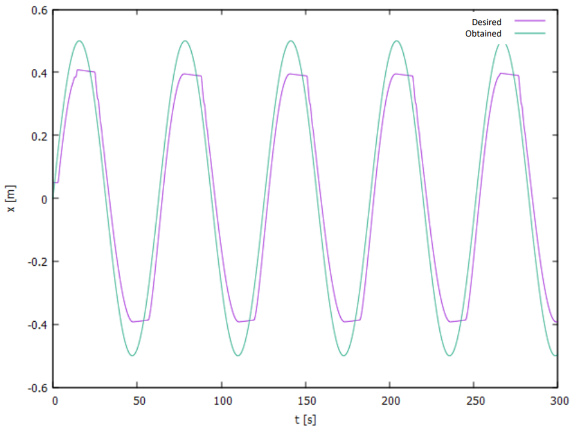

Figure 4. Trajectory tracking by the LR method with dead zone.

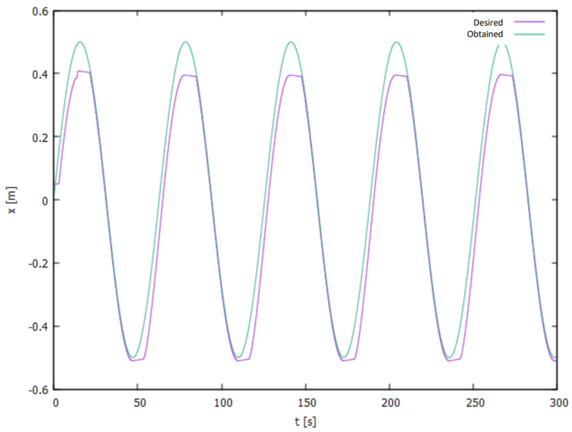

Figure 5. State variable x with equally spaced fuzzy.

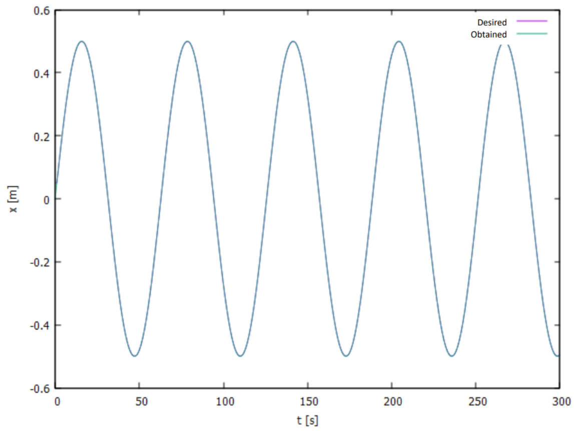

Figure 6. System controlled by FL with fuzzy compensation.

The performance obtained can be visualized in the graphs shown in Fig. (5)-(6). The output response of each rule had its values adopted heuristically, so that $\hat{D}_r = \{-15.0; -3.0; -0.75; 0; 0.75; 3.0; 15.0\}$. It is possible to observe the improvement in the system's trajectory guarantee by the use of heuristically spaced membership functions in the controller and how the control signal also exhibits better stability as shown in Fig. (7)-(8).

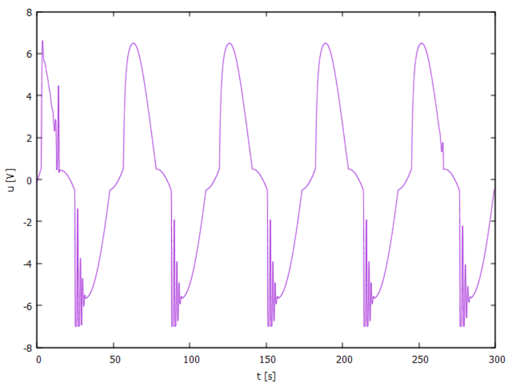

Figure 7. Controlled system without fuzzy compensation.

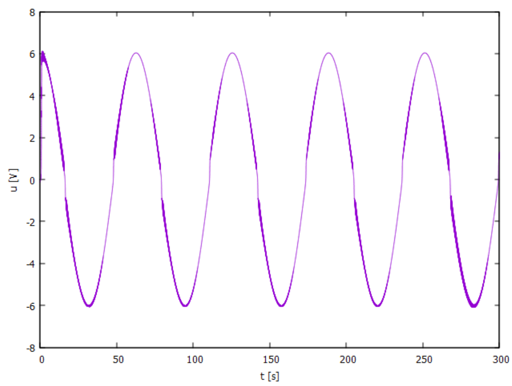

Figure 8. Controlled system with fuzzy compensation.

6.2 Control using sliding modes

Using the same parameters as presented earlier, the controller based on the sliding mode method allows us to observe that the expected trajectory, even with the presence of the dead zone at the system's input, was guaranteed as shown in Fig. (9). However, the manipulated variable u exhibits the phenomenon of chattering, which is excessive high-frequency switching that is harmful to the controlled system Fig. (10). It is worth noting that this simulation was performed with the sign function in its modeling.

To control the manipulated variable u, saturation function was added along with fuzzy compensation, using equally and heuristically spaced membership functions. The central values for the equally spaced case was spaced as follows:

- $C_e = \{-0.005; -0.0033; -0.0016; 0; 0.0016; 0.0033; 0.005\}$ for the error.
- $C_{de} = \{-0.0086; -0.0056; -0.0028; 0; 0.0028; 0.0056; 0.0086\}$ for the error derivative.

In the heuristically spaced case, the following sets were obtained:

- $C_e = \{-0.005; -0.0025; 0.00025; 0; 0.00025; 0.0025; 0.005\}$ for the error.
- $C_{de} = \{-0.0086; -0.0057; -0.0021; 0; 0.0021; 0.0057; 0.0086\}$ for the error derivative.

The values associated with each rule were heuristically determined.

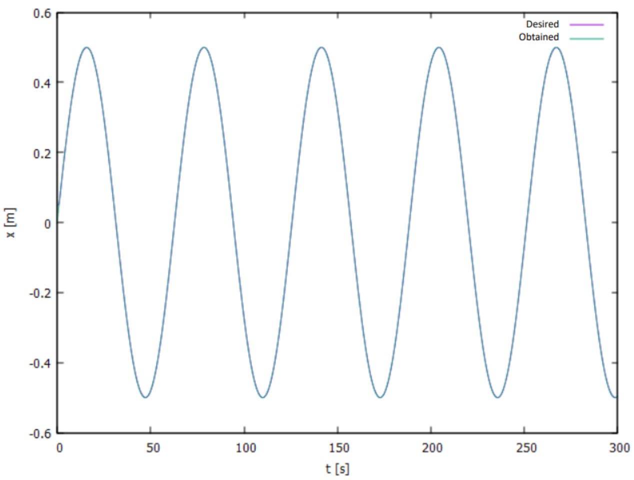

Figure 9. Trajectory tracking by the SM with dead zone.

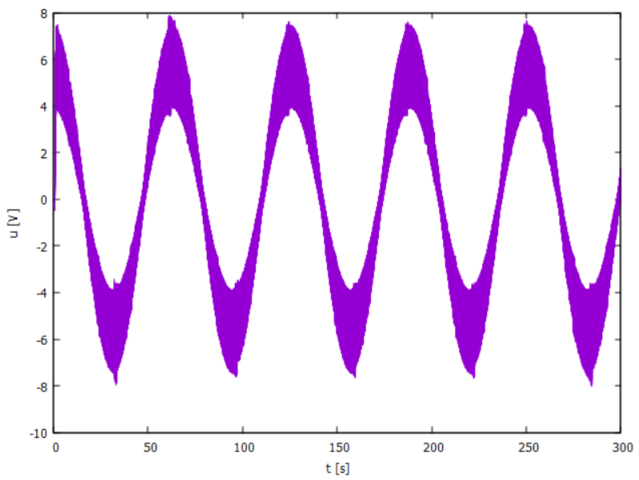

Figure 10. Signal u of the controller.

Through the analysis of the obtained data, is possible to observe the robustness of the sliding mode technique in the face of uncertainties associated with the system and how the chattering phenomenon can be solved by adding the saturation function, as shown in Fig. (11)-(12). However, from the error state space, it is possible to observe a loss of trajectory by the controller in Fig. (13). Fuzzy compensation comes as a solution to this problem, as well as to errors associated with the controller observed in Fig. (14).

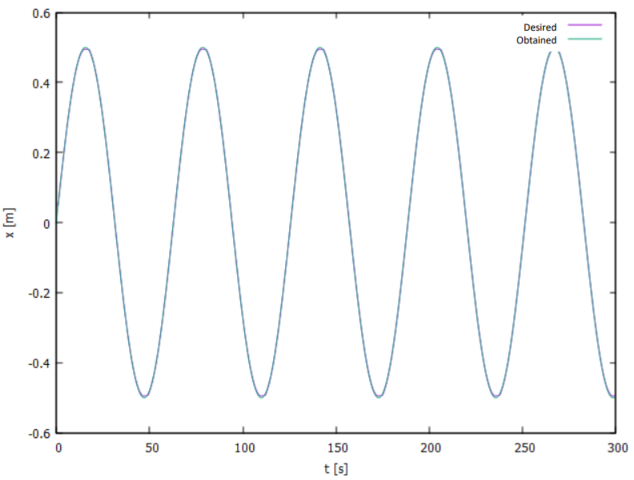

Figure 11. Trajectory tracking by the SM with dead zone.

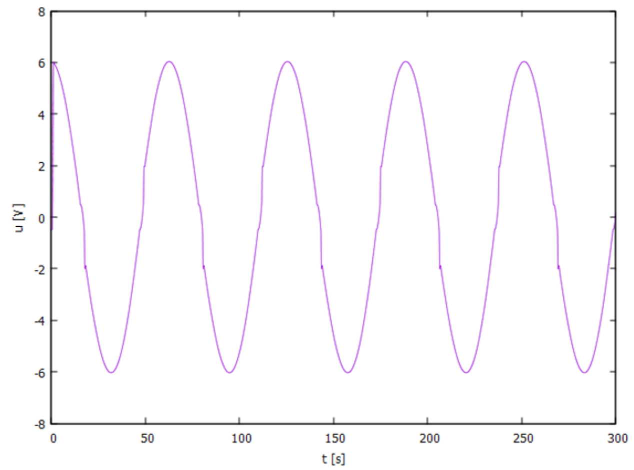

Figure 12. Signal u with saturation function.

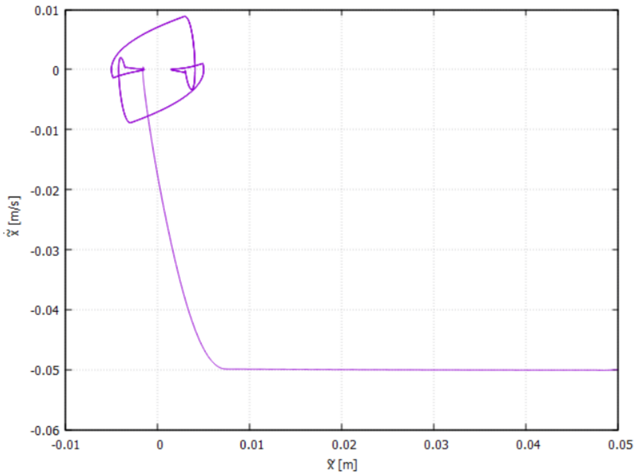

Figure 13. Space-sation with saturation.

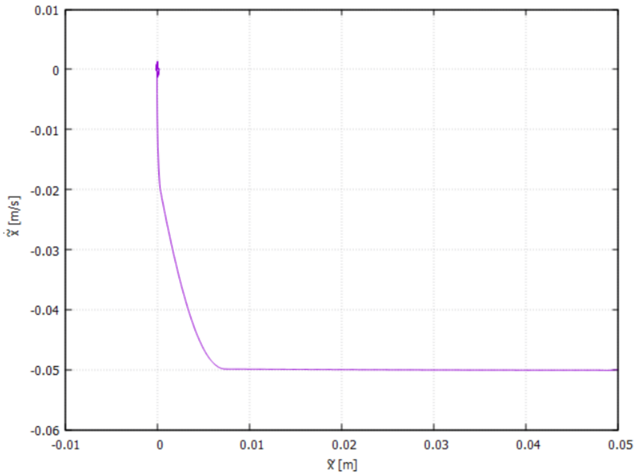

Figure 14. Space-sation with fuzzy compensation.

6.3 Comparison between control techniques and different membership functions

Table (1) shows, through the mean square error (MSE), how both techniques mentioned in this work act in keeping the trajectory and stability of the system. Feedback linearization presents a simpler modeling and easy manipulation, but it loses performance in the face of parameter uncertainties and the occurrence of nonlinearities, such as the dead zone, characteristic of electro-hydraulic systems. The addition of heuristically spaced fuzzy logic improves the performance by approximately 97% compared to its initial condition, showing how heuristic data is more adaptable to guaranteeing the trajectory. However it heavily relies on the designer's experience.

Table 1. **Statistical data for the EHS.**

Controller	MSE [m²]	Difference	Standard deviation [m]
FL	0,0971		0,3065
FL + fuzzy equal.	0,0730	24,82%	0,3413
FL + fuzzy heuris.	0,0022	97,73%	0,3539
SM	0,0029		0,3535
SM + fuzzy equal.	0,0018	38%	0,3541

The controller using the technique of sliding modes presents a better response to the inherent uncertainties of the system when compared to linearization by feedback, however it presents more complex modeling. Moreover, due to the addition of the sliding surface, it allows the occurrence of the phenomenon of chattering , which can cause damage to the actuators due to the intensity of this control signal. The addition of the saturation function and fuzzy compensation solves this problem and others associated with trajectory loss.

7. CONCLUSION

This work presents two nonlinear controllers based on feedback linearization and sliding mode techniques, with compensation using fuzzy logic. It can be observed that controllers using feedback linearization present a simpler and easier-to-handle modeling, but they lose performance in the presence of parameter uncertainties and nonlinearities, such as the dead zone, present in electro-hydraulic systems.

The controller using sliding mode technique shows a better response to the inherent uncertainties of the system when compared to feedback linearization, but it has a more complex modeling. Due to the addition of the sliding surface, it allows the occurrence of chattering phenomenon, which can cause damage to actuators due to the intensity of this control signal. This phenomenon could be eliminated by replacing the sign function with a saturation function, but it results in a loss of trajectory performance.

By applying artificial intelligence techniques, it is possible to correct the performance loss and failure of the controllers, but it adds greater complexity to the design. Furthermore, it can be observed that using heuristically spaced membership functions leads to better convergence and reduction of the error from the desired trajectory, as the controller gain decreases, ensuring that the obtained error does not exceed the zero point by a large margin. However, this decision depends on designer experience.

8. ACKNOWLEDGEMENTS

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10. RESPONSIBILITY NOTICE