Performance comparison of optimization techniques in EHS system using sliding mode controller

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Abstract. Electro-Hydraulic Servo (EHS) system is a well-known nonlinear system in various types of industries due to its outstanding characteristics over other actuators. Despite its wide applications in industries, this system also suffering from nonlinearities and parameter uncertainties. Sliding Mode Controller (SMC) has been proven by many researchers to be effective in positioning control of the nonlinear system. However, SMC controller parameters must be tuned in appropriate ways to control the EHS system. In this research, an SMC strategy which combines with an enhanced PSO called Multi-Objective Particle Swarm Optimization (MOPSO) is proposed in positioning control of the EHS system. The conventional PSO is design as well for comparison purpose. The output performance is analysed and verified using different performance indexes such as rise time, settling time, overshoot percentage, and root mean square error. The results show that the MOPSO is better in tuning the controller parameters.

1. Introduction

Electro-Hydraulic Servo (EHS) systems are widely used in today’s applications such as manufacturing industry, automotive, earthmoving vehicles, aerospace industry, and robotic manipulators [1]. EHS has always been chosen to be the actuator because of its advantages over other types of actuators such as electric motor and pneumatic actuator. The main advantages of the EHS system are high power to weight ratio and large force capabilities [2].

Despite the advantages and various applications of the EHS system, EHS system suffers from nonlinearities and parameter uncertainties which led to the degradation of the actuator performance. These are caused by fluid leakage in actuators, frictions, pressure-flow characteristics, oil temperature, and load stiffness [3]–[6].

In recent years, many researchers have proposed different types of control strategies in positioning control of the EHS system. However, Sliding Mode Controller (SMC) has been proven to be outstanding over other controllers in providing robust performance for the nonlinear dynamic system [7], [8]. Therefore, SMC will be chosen for EHS system positioning control in this research.

The aim of this research is to tune the best controller parameters in SMC in order to get the desired output performance of EHS system. According to [9], the tuning problem of controller gains can be considered as an optimization problem. In this research, two types of optimization techniques are used in tuning SMC parameters which are conventional PSO and MOPSO.
The rest of the paper is structured as follows: Section 2 will discuss the EHS system model used in this research. Section 3 will explain the proposed control strategies. Section 4 will analyze and discuss the results and finally, a conclusion is to draw in section 5.

2. EHS System Modelling
The main objective of this research is to control the EHS system in terms of position control. The mathematical modeling is utilized in this research. Figure 1 shows the physical model of the EHS system used in this research.

\[ F_p = A_p (P_1 - P_2) = M_p \frac{d^2x_p}{dt^2} + B_s \frac{dx_p}{dt} + K_s x_p + F_f \]  

(1)

The EHS system parameters used in this research are tabulated in Table 1.

| Symbol | Description                        | Value       |
|--------|------------------------------------|-------------|
| \( I_{sat} \) | Torque motor saturation current | 0.02 A      |
| \( L_c \) | Servo-valve coil inductance        | 0.59 H      |
| \( R_c \) | Servo-valve coil resistance        | 100 Ω       |
| \( \beta \) | Hydraulic fluid bulk modulus      | 1.4x10^9 N/m² |
| \( \omega_n \) | Servo-valve natural frequency     | 543 rad/s   |
| \( \xi \) | Servo-valve damping ratio          | 0.48        |
| \( P_r \) | Return pressure                    | 0 Pa        |
| \( P_s \) | Pump pressure                      | 2.1x10^7 Pa |
| \( K \) | Servo-valve gain                   | 2.38x10^-5 m³/²/kg¹/² |
| \( M_p \) | Total mass                         | 9 kg        |
| \( X_s \) | Total actuator displacement        | 0.1 m       |
| \( B_s \) | Damping coefficient                | 2000 Ns/m   |
3. Proposed Control Strategies

In this research, a nonlinear SMC will be used in positioning control of the EHS system. Two optimization approaches which are PSO and MOPSO will be utilized and compared in this research for tuning the SMC parameters.

a. Sliding Mode Controller (SMC)

Sliding Mode Control is introduced in the early ’60s in Russia. The most important step in designing an SMC is the construction of an appropriate sliding surface. The sliding surface, \( s(t) \) used in this research is expressed in equation (2).

\[
 s(t) = (\lambda + \frac{d}{dt})^{n-1}e(t)
\]  

(2)

where \( \lambda \) = positive constant  
\( n \) = model order of the system to be controlled  
\( e(t) \) = tracking error

The control signal of SMC is divided into two parts: equivalent control and switching control. The equivalent control and switching control in SMC are corresponding to the sliding and reaching phase. Both the equivalent control and switching control are expressed in the equations (3) and (4).

\[
 u_{eq}(t) = \frac{1}{C} (\ddot{x} + A_n \dot{x} + B_n \dot{\dot{x}}) + 2*\lambda*\ddot{e}(t) + \lambda^2*\dot{e}(t)
\]  

(3)

\[
 u_{sw}(t) = k_s * \tanh\left(\frac{\ddot{x}}{\varphi}\right)
\]  

(4)

Finally, both control signals are added together to produce the total control signal of SMC.

\[
 u_{smc}(t) = \frac{1}{C} (\ddot{x} + A_n \dot{x} + B_n \dot{\dot{x}}) + 2*\lambda*\ddot{e}(t) + \lambda^2*\dot{e}(t) + k_s * \tanh\left(\frac{\ddot{x}}{\varphi}\right)
\]  

(5)

From the equation (5), there are two parameters which are \( \lambda \) and \( \varphi \) that need to be tuned in SMC. The proposed optimization processes will be discussed in next subsections.

b. Conventional Particle Swarm Optimization (PSO)

PSO is proposed in this research to tune the SMC parameters, \( \lambda \) and \( \varphi \). Conventional PSO is introduced by Kennedy and Eberhart in 1995. The idea of this optimization came from fish schooling and bird flocking while searching for foods [11].

In PSO, a random particles population called swarm is flying around a global searching space to search for the best particles using the position and velocity information of each particle. Equations (6) and (7) show the position and velocity used in this research.

\[
x^{i+1} = x^i + v^{i+1}
\]  

(6)

\[
v^{i+1} = \omega v^i + c_1 r_1 (P_{BEST}^i - x^i) + c_2 r_2 (G_{BEST} - x^i)
\]  

(7)

The position and velocity of each particle will change every iteration according to the given fitness equation. In conventional PSO, there is just one objective function in the fitness equation to be achieved. In this research, the error calculated from the EHS system performance will be the objective function in conventional PSO. The equation (8) shows the fitness equation used in this conventional PSO.

\[
 fitness\_equation = error
\]  

(8)

c. Multi-Objective Particle Swarm Optimization (MOPSO)

MOPSO is an enhanced version of conventional PSO. The only difference between the MOPSO and the conventional PSO is that MOPSO has two objective functions in its fitness equation. The objective
functions to be achieved through MOPSO in this research will be the error and the overshoot calculated from the EHS system performance.

The intention to add in one more objective function is to make the conventional PSO become more effective when it selects the controller parameters. The fitness equation used in this MOPSO is expressed in equation (9).

\[
    \text{fitness equation} = \text{error} + \text{overshoot}
\]  

(9)

4. Results and Discussion

In order to test the performance of the EHS system using both PSO-SMC and MOPSO-SMC controllers, a step input is fed into the EHS system. The performance of the EHS system is analyzed using different types of the performance index.

Table 2. The output performance analysis of EHS system.

| Analysis | Rise Time (s) | Settling Time(s) | Overshoot Percentage (%) | Root Mean Square Error (mm) |
|----------|---------------|------------------|---------------------------|-----------------------------|
| PSO-SMC  | 0.0250        | 0.0460           | 0.9504                    | 1.29                        |
| MOPSO-SMC| 0.0380        | 0.0670           | 0.1518                    | 1.45                        |

Table 2 shows the output performance analysis of the EHS system. The analysis is done by using several performance indexes normally used in control system such as the rise time, settling time, overshoot percentage and finally, the root mean squared error. From the table, both the rise time and the settling time are smaller than 0.1 second which is in the acceptable range. For the root mean square error, PSO-SMC has a root mean square error value smaller than the MOPSO-SMC. This shows that the PSO-SMC is performed better and less error than the MOPSO-SMC.

However, it is obviously in table 2 that the overshoot percentage of the PSO-SMC is much higher than the MOPSO-SMC. PSO-SMC has a value of 0.9504% of overshoot percentage while the MOPSO-SMC only recorded 0.1518%. Higher overshoot means the EHS actuator will move beyond the desired value before settles down to the desired value. This proved that MOPSO-SMC will not have to move to a very high value as compared to PSO-SMC before settles down to the desired value. The biggest disadvantage of moving too much beyond the desired value will possibly cause damage to the EHS actuator.
Figure 2 shows the results of the output performance of the EHS system. The red line denoted the PSO-SMC while the blue line denoted the MOPSO-SMC. It is obvious from the figure that the overshoot of the PSO-SMC is higher than the MOPSO-SMC. There is a little chattering for the PSO-SMC as seen from figure 2 in which does not appear in the MOPSO-SMC.

5. Conclusion
Two types of optimization techniques are presented in this research to tune the SMC parameters in positioning control of the EHS system. One of it is conventional PSO combined with SMC and another one is an enhanced version of PSO called MOPSO paired with SMC. Both optimization techniques are applied in the simulation and output performance of the EHS system is analyzed. From the results, it shows that the MOPSO-SMC are performed better than the PSO-SMC. The additional objective function in MOPSO is shown to affect the final output performance of the EHS system in terms of overshoot percentage. The final output performance has an obvious degradation in overshoot percentage as compared to the conventional PSO which only has an objective function.

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References
[1] Y. Yoon, Z. Sun, and H. Du, “Inverse Modeling Approach for Parametric Frequency Domain Analysis of An Electrohydraulic System,” Mech. Syst. Signal Process., vol. 121, pp. 412–425, 2019.
[2] W. Ma, W. Deng, and J. Yao, “Continuous Integral Robust Control of Electro-Hydraulic Systems with Modeling Uncertainties,” IEEE Access, vol. 6, pp. 46146–46156, 2018.
[3] S. M. Othman, M. F. Rahmat, S. M. Rozali, and S. Salleh, “Review on Sliding Mode Control and Its Application in Electrohydraulic Actuator System,” J. Theor. Appl. Inf. Technol., vol. 77, no. 2, pp. 199–208, 2015.
[4] E. K. Gdoura, M. Feki, and N. Derbel, “Sliding Mode Control of A Hydraulic Servo System Position Using Adaptive Sliding Surface and Adaptive Gain,” Int. J. Model. Identif. Control, vol. 23, no. 3, p. 248, 2015.
[5] 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 Trans. Ind. Electron., vol. 63, no. 11, pp. 6909–6920, 2016.
[6] S. Wang, Q. Xu, R. Lin, M. Yang, W. Zheng, and Z. Wang, “Feedback Linearization Control for Electro-Hydraulic Servo System Based on Nonlinear Disturbance Observer,” in Chinese Control Conference, CCC, 2017, pp. 4940–4945.
[7] Y. Liu and H. Handroos, “Technical Note Sliding Mode Control for A Class of Hydraulic Position Servo,” Mechatronics, vol. 9, no. 1, pp. 111–123, 1999.
[8] A. Bonchis, P. I. Corke, and D. C. Rye, “Experimental Evaluation of Position Control Methods for Hydraulic Systems,” IEEE Trans. Control Syst. Technol., vol. 10, no. 6, pp. 876–882, 2002.
[9] M. Y. Kim and C. O. Lee, “An Experimental Study on The Optimization Of Controller Gains for An Electro-Hydraulic Servo System Using Evolution Strategies,” Control Eng. Pract., vol. 14, no. 2, pp. 137–147, 2006.
[10] M. Kalyoncu and M. Haydim, “Mathematical Modelling and Fuzzy Logic Based Position Control of An Electrohydraulic Servosystem with Internal Leakage,” Mechatronics, vol. 19, no. 6, pp. 847–858, 2009.
[11] J. Kennedy and R. Eberhart, “Particle Swarm Optimization,” Neural Networks, 1995. Proceedings., IEEE Int. Conf., vol. 4, pp. 1942–1948, 1995.