Optimized Fuzzy Sliding Mode Control to Enhance Chattering Reduction for Nonlinear Electro-Hydraulic Servo System

Muhammad Babar Nazir and Shaoping Wang

Abstract

Variable structure control with sliding mode can provide fine control performance and robustness. However, chattering phenomenon introduced due to discontinuous switching gain limits their applications. To achieve precise tracking performance with reduced chattering effect, fuzzy sliding mode control is introduced and evolutionary simultaneous tuning of control parameters is employed. Novel evolutionary algorithm (NEA) is applied for simultaneous optimization process due to its computational efficiency and reliability. Chattering reduction issue is further improved by introducing the weighting factors estimation technique. In this technique, weighting factors for each control term are estimated with the objective to provide control action according to desired response. The integrated weighted control action not only reduces the chattering amplitude but also improves the tracking performance. The proposed techniques are applied to nonlinear electro-hydraulic servo system. Extensive simulation and experiment results indicate that proposed schemes not only improve the tracking performance but also ensure chattering reduction. Further, controller developed based on proposed schemes sustains the performance under parametric uncertainties and disturbances.

Keywords: Chattering reduction, novel evolutionary algorithm, fuzzy sliding mode control, simultaneous optimization.

1. Introduction

Variable structure control (VSC) with sliding mode also called sliding mode control (SMC) fascinates the attentions due to its robustness against parametric uncertainties and unmodeled dynamics. However, there is associated a major drawback called chattering, which is instigated due to discontinuous switching gain in the SMC. Chattering is undesirable as it degrades the control performance by motivating the unmodeled system dynamics [1-3]. So, how to decrease the chattering is urgent to solution in SMC design. During past two decades, numerous techniques had been studied for chattering reduction. Boundary layer [2] approach can reduce chattering but at the cost of robustness. Hence, it is necessary to get the compromise between robustness and chattering reduction [1, 2]. Eloi Z. Taha [4] presented the concept of quantitative feedback theory (QFT); Luigi lannelli [5] used dither approach; Pushkin Kachroo [6] exploited integral action inside fixed boundary layer for chattering reduction. In recent years, fuzzy logic [1, 7-15] was widely used to reduce chattering effect and improve the tracking performance. However, major problem encountered for fuzzy based sliding mode control is how to select the most appropriate controller parameters.

This research work presents novel evolutionary based fuzzy sliding mode control (FSMC) with the objectives of reducing the chattering amplitude and achieving precise tracking performance for nonlinear electro hydraulic servo system (EHSS). In order to account for main nonlinear effect, LuGre dynamic friction model is incorporated in mathematical modeling of nonlinear EHSS. Novel evolutionary algorithm (NEA) is applied for simultaneous optimization process due to its computational efficiency and reliability [16, 17]. The objective function for optimization is developed, which takes into consideration both the effect of tracking error and chattering to optimize the solution. The most significant feature of the research is the evolutionary estimation of weighting factors for SMC and fuzzy control terms, which ensure the chattering attenuation with improved tracking performance. Extensive simulation and experimental results acquired authenticate the effectiveness and robustness of proposed controller under parametric uncertainties, unknown modeling error and external disturbances.

The rest of paper is organized as: section 2 establishes the mathematical model of EHSS. Section 3 focuses on the development of SMC. Section 4 presents the fuzzy sliding mode control. Section 5 gives the novel evolutionary optimization of fuzzy sliding mode control. Section 6 demonstrates application of proposed

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technique for nonlinear EHSS and conscientious comparison is made with other techniques to illustrate the effectiveness of proposed controller. Further, effectiveness of the proposed technique is validated through experiments. Finally, section 7 gives the conclusions.

2. Mathematical Modeling of Nonlinear EHSS

A typical EHSS consists of servo valve, hydraulic motor, load and sensors [17, 18] as shown in figure 1.

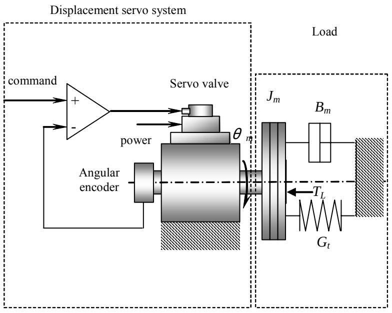

Figure 1. Structure of hydraulic displacement control system.

Servo valve acts as the interface between electrical power and hydraulic power. Valve dynamics are approximated as second order system and relation of spool displacement (x_v) to the input current (i) is given as:

$$G(s)=\frac{x_v}{i}=\frac{K_v}{\frac{s^2}{\omega^2}+\frac{2\xi s}{\omega}+1} \tag{1}$$

where x_v is the displacement of spool; i is the current input; K_v is the spool displacement coefficient of servo valve; ω is the inherent frequency of servo valve; ξ is the damping coefficient.

Nonlinear load flow of servo valve neglecting leakage is given as:

$$Q_f = C_v W x_v \sqrt{\frac{p_s - \operatorname{sgn}(x_v) p_f}{\rho}} \tag{2}$$

where Q_f is the load flow; C_v is the coefficient of discharge, W is the area gradient, x_v is the displacement of the spool, p_s is the supply pressure, p_f is the load pressure and ρ is the fluid mass density.

The flow of hydraulic motor can be depicted as:

$$Q_f = D_m \frac{d\theta_m}{dt} + \frac{V_m}{4E_y}\frac{dp_f}{dt} + C_{tm} p_f \tag{3}$$

The torque balance equation is given as:

$$D_m p_f = J_m \frac{d^2\theta_m}{dt^2} + B_m \frac{d\theta_m}{dt} + G_t\theta_m + T_f \tag{4}$$

where D_m is the volumetric displacement of motor, θ_m is the angular position of motor, V_m is the total volume of motor chamber, E_y is the effective bulk modulus, C_{tm} is the leakage coefficient of motor, J_m is the inertia of motor, B_m is the viscous damping coefficient of load, G_t is the equivalent torsional spring gradient of load and T_f is the friction torque.

Friction has very strong influence on the performance especially at low velocity [1, 19, 20], so it is taken as an external disturbance in the mathematical model. LuGre dynamic friction model is considered here because it can describe the sliding displacement, memorial friction, variable static friction and viscous friction synchronously. It is inspired by the bristle interpretation of friction. Hence, it is derived by integrating the Dahl model and the bristle model [19].

LuGre model consists of four static parameters and two dynamic parameters along with an immeasurable internal state describing the average behavior of bristles. The mathematical description is explained in proceeding section. The equation of friction torque is given as:

$$T_f = \sigma_0 z + \sigma_1 \frac{dz}{dt} + \sigma_2 \dot{\theta}_m \tag{5}$$

where T_f is the friction torque, σ_0 is stiffness coefficient, σ_1 is damping coefficient, σ_2 is viscous coefficient, $\dot{\theta}_m$ is angular velocity of motor, z is the dynamics of the friction internal state whose differential coefficient can be described as:

$$\frac{dz}{dt} = \dot{z} = \dot{\theta}_m - \frac{\left|\dot{\theta}_m\right|}{g\left(\dot{\theta}_m\right)} z \tag{6}$$

where function $g\left(\dot{\theta}_m\right)$ describes part of the "steady –state" characteristics of the model for the constant velocity motion

$$g\left(\dot{\theta}_m\right) = \frac{1}{\sigma_0}\left[T_c + \left(T_s - T_c\right) e^{-\left(\dot{\theta}_m/\dot{\theta}_s\right)^2}\right] \tag{7}$$

where T_c is the coulomb friction torque, T_s is static friction torque and $\dot{\theta}_s$ is the stribeck velocity.

3. SMC Development for Nonlinear EHSS

Sliding mode control is a state feedback control scheme [1, 2], as is illustrated in figure 3, and is robust to unmodeled dynamics. So, to use SMC for controller design a 3rd order model is derived by combining (1)-(4) and neglecting the servo valve dynamics as:

$$\begin{aligned} \dot{x}_1 &= x_2(t) \\ \dot{x}_2 &= x_3(t) \\ \dot{x}_3 &= f(x,t)+b(x)u(t)+d(t) \\ \dot{x}_3 &= -\sum_{i=1}^{3} a_i(t)x_i(t)+b(x)u(t)+d(t) \end{aligned} \tag{8}$$

where

$$[x_1x_2x_3]^T = [\theta_m\dot{\theta}_m\ddot{\theta}_m]^T$$

θ_m is the angular position of the motor, $\dot{\theta}_m$ is the angular velocity of motor, $\ddot{\theta}_m$ is the angular acceleration of motor, $f(x,t)$ is the nonlinear dynamics, $b(x)$ is the control gain, $u(t)$ is the control voltage, $d(t)$ is the disturbance.

Let:

$$a_1 = \frac{4E_y}{V_m}\frac{C_{tm}}{J_m}G_t\,,\quad a_2 = \frac{4E_yD_m^2}{V_mJ_m}+\frac{G_t}{J_m}\,, a_3 = \frac{4E_y}{V_m}\frac{C_{tm}}{J_m}$$

$$b = \frac{4E_yD_m}{V_mJ_m}K_vC_vW\sqrt{\frac{p_s - \mathrm{sgn}(x_v)p_f}{\rho}}$$

$$d(t) = -\frac{4E_y}{V_m}\frac{C_{tm}}{J_m}T_e - \frac{1}{J_m}\dot{T}_e$$

It is almost impossible to know exactly the system dynamics, control gain and disturbance. However, to have reasonable approximations following assumptions are made.

$$\begin{aligned} &b(x,t) = \hat{b}(x)+\Delta b(x,t) \\ &\left|f(x,t)-\hat{f}(x,t)\right| \le F(x,t) \\ &d(t) < D \end{aligned} \tag{9}$$

where $\hat{b}(x)$ represents nominal parameters of the system, and $\Delta b(x,t)$ are parameter uncertainties, $F(x,t)$ is a known function representing the bound on the error between unknown dynamics $f(x,t)$ and estimated dynamics $\hat{f}(x,t)$, $d(t)$ are disturbances. The bounds of control gain can be given as:

$$0 < b_{\min} \le b \le b_{\max} \tag{10}$$

Here control gain has the multiplicative effect, so estimated control gain $\hat{b}$ is selected as geometrical mean of upper and lower bounds of b as:

$$\hat{b} = \sqrt{b_{\min}b_{\max}} \tag{11}$$

Tracking error is defined as $e_\theta = \theta_m - \theta_d$ and state error vector is given as:

$$e = [e_\theta e_{\dot{\theta}} e_{\ddot{\theta}}]^T \tag{12}$$

where $e_\theta = \theta_m - \theta_d$; $e_{\dot{\theta}} = \dot{\theta}_m - \dot{\theta}_d$; $e_{\ddot{\theta}} = \ddot{\theta}_m - \ddot{\theta}_d$; θ_d is desired angular position, $\dot{\theta}_d$ is desired angular velocity, $\ddot{\theta}_d$ is desired angular acceleration.

Switching function is defined with the objective of achieving fine control performance and is given as:

$$S(e,t) = \left(\frac{d}{dt}+\lambda\right)^2 e_\theta = \lambda^2 e_\theta + 2\lambda e_{\dot{\theta}} + e_{\ddot{\theta}} \tag{13}$$

where $\lambda > 0$ is constant and its value is selected according to desired system performance.

The equivalent control u_{eq} is a linear feedback of states that causes the states to move toward and reach sliding surface. So, it is determined from the necessary condition of $\dot{S} = 0$ without uncertainties and disturbance and is given as:

$$u_{eq} = \hat{b}^{-1}\left(\dddot{\theta}_d - \hat{f}(x,t) - \lambda^2 e_{\dot{\theta}} - 2\lambda e_{\ddot{\theta}}\right) \tag{14}$$

To accommodate the estimation error, a discontinuous term is added in control command which causes the states to remain on sliding surface:

$$u = u_{eq} + u_{sw} \tag{15}$$

$$u_{sw} = -\hat{b}^{-1}K_{sw}sg(s) \tag{16}$$

In essence, all system trajectories must be forced to converge to S in finite time and to remain on S afterwards so as to achieve a zero tracking error. Letting Lyapunov function as $V = 0.5S^2$, the reaching condition can be described as:

$$\dot{V} = \frac{1}{2}\frac{d}{dt}S^2(e,t) \le -\eta\left|S(e,t)\right| \tag{17}$$

where η is strictly positive design parameter. This is equivalent to:

$$S(e,t)\dot{S}(e,t) \le -\eta\left|S(e,t)\right| \tag{18}$$

Switching gain K_{sw} is determined such that (18) is satisfied. The final condition for K_{sw} is:

$$K_{sw} \ge \beta(F+\eta) + (\beta-1)\hat{b}\left|U\right| + D \tag{19}$$

where $|d| \le D, \left|u_{eq}\right| \le U, \left|f - \hat{f}\right| \le F$

Discontinuous switching gain results in chattering that can be reduced by introducing boundary layer.

$$u_{sw} = -\hat{b}^{-1}K_{sw}\tanh(S/\phi) \tag{20}$$

where $\phi > 0$ is the boundary layer thickness and its value can be adjusted according to desired system performance.

The performance of conventional SMC is evaluated for system described in section 2. Supposing the fluctuation range for the coefficients of state equation to be 50%, the bounds of uncertainties and estimation error can be evaluated as follows:

$$\beta = \sqrt{\frac{b_{\max}}{b_{\min}}} = \sqrt{3}, F = \left|f - \hat{f}\right| = 0.5\left|\hat{f}\right| \tag{21}$$

Tracking performance is illustrated in figure 2, where curve 1 represents nominal conditions, curve 2 represents increased friction effect, curve 3 represents parameter variation and curve 4 illustrates disturbance effect. The objective of performance evaluation under different effects is illustrated in section 6.

Simulation results indicate that the dynamic performance with SMC is good and robust except the existence of chattering. Discontinuity in switching control may excite the unmodeled dynamics and thus cause chattering, which is undesirable as it degrades the performance. So, how to achieve precise tracking performance with reduce chattering amplitude is the main objective of this research work.

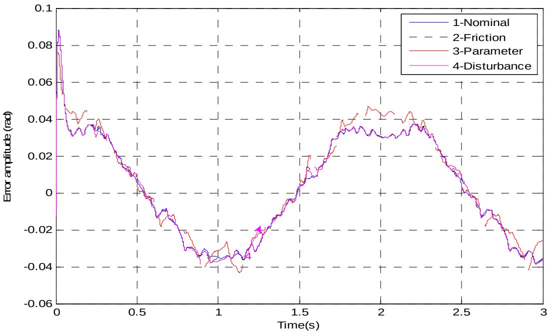

Figure 2. Comparison of tracking error with SMC.

4. Fuzzy Sliding Mode Control

In the preceding discussion, it has been determined that the main source of chattering is the discontinuous switching control action. Therefore, a fuzzy logic control is integrated with conventional SMC to reduce intrinsic chattering effect and improve performance. To further suppress the chattering amplitude, a new approach is presented which is based on weighting the control action. In the proposed technique specific weighting factors for each control term are estimated with the objective to provide the control action according to desired response. The integrated weighted control action not only reduces the chattering amplitude but also improves the tracking performance.

Fuzzy controller acts complementary to SMC and total control action with weighting factors is given by:

$$u = w_{eq}u_{eq} + w_{sw}u_{sw} + w_f u_f \tag{22}$$

where u_{eq} is the equivalent control responsible for moving the states to sliding surface, u_{sw} is the switching control responsible for forcing the states to remain on sliding surface and also instigates the chattering effect, u_f is the fuzzy control action whose design procedure will be explained in proceeding discussion. w_{eq} , w_{sw} and w_f are the weighting factors for equivalent control, switching control and fuzzy control respectively.

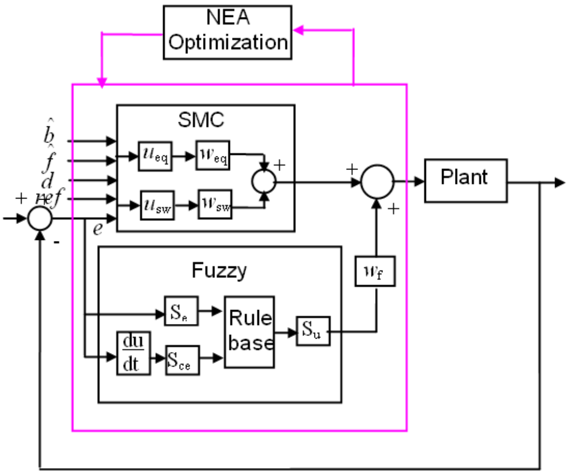

Figure 3. Schematic diagram of FSMC with optimization scheme.

Tracking error and time rate change of tracking error are selected as input variables and control voltage as output variable for fuzzy control as explained in figure 3. The design process can be categorized into different phases and can be described as:

Fuzzification phase: This phase converts the real value into fuzzy sets. Triangular membership functions (MFs) are employed to quantify the meanings of linguistic values [21] for input and output variables as shown in figures 6, 7 and 8 respectively. These are selected due to their computational efficiency and better control performance. Further, nonlinear scaling factors are employed to map the variables into universe of discourse.

Fuzzy rules: These describe the quantitative relationship between variables in linguistic terms [22]. The rule base of fuzzy system is developed with the aim to achieve precise tracking performance and attenuate chattering effects. For this specific research fuzzy rule base consists of 15 rules, which are calculated as:

$$R_t = l_{in1} \times l_{in2} \tag{23}$$

where $R_t = 15$ represents total rules, $l_{in1} = 5$ and $l_{in2} = 3$ represents the number of linguistic terms for error and change error respectively. The set of fuzzy rules are given in table 1.

Table 1. Rule base for fuzzy control.

Change error	Error				
	NB	NM	ZE	PM	PB
N	NB	NM	NS	PS	PS
ZE	NM	NS	ZE	PS	PM
P	NS	NS	PS	PM	PB

Inference phase: In this phase overall fuzzy control output is computed based on the individual contribution of each rule in the rule base. Direct inference technique is employed for this research study.

Defuzzification phase: In this phase a real value is produced from the result of inference, which is termed as fuzzy incremental control input. Centre of gravity technique is used due to its computational efficiency.

$$u_{fin} = \frac{\sum_{i=1}^{15}\{\mu(input_i)\times output_i\}}{\sum_{i=1}^{15}\{\mu(input_i)\}} \qquad (24)$$

where i is the rule number and μ is the membership value.

Fuzzy incremental control input is then denormalized using nonlinear scaling factor to obtain the real control input.

Performance of FSMC is evaluated and simulation results are illustrated in figure 4, where the performance is improved but still not content. The major obstacle to achieve the precise tracking performance with reduced chattering effect is the proper selection of control parameters which strongly influence the control performance.

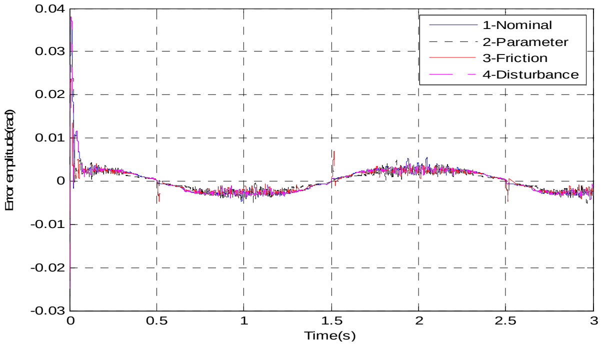

Figure 4. Comparison of tracking error with FSMC.

So, to cope with all these difficulties, evolutionary estimation of control parameters is presented with the objectives of achieving precise tracking performance and reduction in chattering amplitude.

5. Evolutionary Optimization

NEA evaluates more than one area of search space and can discover more than one solution to a problem. Typical functions involve are population initialization, fitness evaluation, crossover, mutation and alternate generation [16]. Typical flow diagram [23] is shown in figure 5.

In proceeding section, NEA is applied to optimize simultaneously the control parameters for fuzzy and SMC control logics. The object variables with their specific domain and notations are given in table 2. Figure 6 and figure 7 illustrate the selection of parameters to be optimized for error and change error MFs respectively.

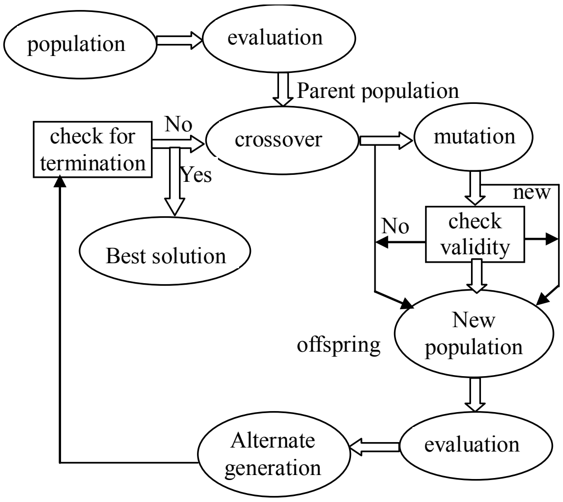

Figure 5. Work flow diagram of NEA.

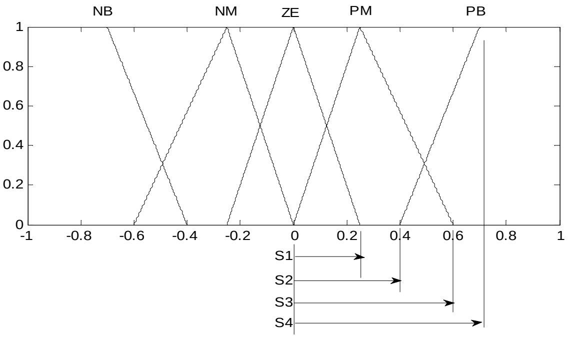

Figure 6. Triangular membership functions for error with optimization scheme.

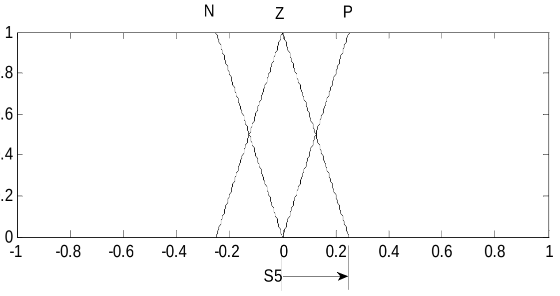

Figure 7. Triangular membership functions for change error with optimization scheme.

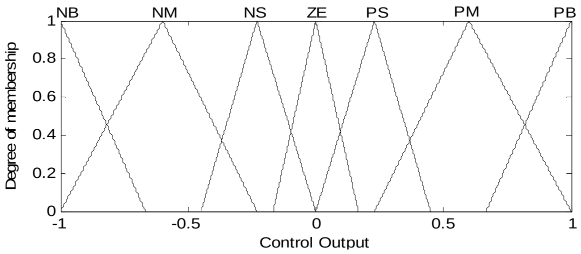

Figure 8. Triangular membership functions for output.

Table 2. Object variables for optimization.

Object variables for optimization of fuzzy sliding mode			
Fuzzy	MFs Distribution (S_1 _ S_5)	Scaling Factors (Se, Sce, Si)	Weighting factor (w_f)
	$S_1 \in [0.1,0.2]$ $S_2 \in [0.2,0.3]$ $S_3 \in [0.35,0.45]$ $S_4 \in [0.5,0.65]$ $S_5 \in [0.05,0.15]$	$S_6 \in [400,500]$ $S_7 \in [10,100]$ $S_8 \in [2.5e3,3e3]$	$S_9 \in [0.7,0.85]$
SMC	Lambda (λ)	Boundary layer (ϕ)	Weighting factor (w_{sw})
	$S_{10} \in [85,100]$	$S_{11} \in [0.1,0.5]$	$S_{12} \in [0.3,0.5]$

The application of novel evolutionary algorithm for fuzzy SMC works as follows:

(1) The initial population for object variables is initialized randomly using a uniform random number (URN) within the desired domains and consists of $\mu_j = 40$ individuals each. This initialized population is considered as parent population for next generation after evaluating the individuals μ_i to their cost function.

(2) In this phase Subpopulations-Based Max-mean Arithmetical Crossover (SBMAC) concept is used to reduce the genetic variations and make algorithm computationally fast. The individuals are ordered according to their cost functions and then the parent population P (t) is divided into $l=4$ subpopulations in each generation t such that each subpopulation has $\mu_j / l = 10$ individuals. The first individual of each object variables of *i*th subpopulation is selected as an elite individual $\psi_{i,\max}^{t}$ (Mom), at generation *t*, because it maximized a cost function within *i*th subpopulation, and a mean individual $\overline{\psi}_{i,mean}^{t}$ (Dad) is created from the remaining individuals of *i*th subpopulation excluding the $\psi_{i,\max}^{t}$.

The crossover operation is defined to produce two offspring (ζ_1^t, ζ_2^t) as:

$$\zeta_1^t = \Big(\alpha_1 S_{1(i,\max)} + (1-\alpha_1)\overline{S}_{1(i,mean)},\ \alpha_2 S_{2(i,\max)} + (1-\alpha_2)\overline{S}_{2(i,mean)}, \ldots, \alpha_{12} S_{12(i,\max)} + (1-\alpha_{12})\overline{S}_{12(i,mean)}\Big) \tag{25}$$

$$\zeta_2^t = \Big((1-\alpha_1) S_{1(i,\max)} + \alpha_1 \overline{S}_{1(i,mean)},\ (1-\alpha_2) S_{2(i,\max)} + \alpha_2 \overline{S}_{2(i,mean)}, \ldots, (1-\alpha_{12}) S_{12(i,\max)} + \alpha_{12} \overline{S}_{12(i,mean)}\Big) \tag{26}$$

where $s_1, s_2, s_3, \ldots, s_{12}$ represent the object variables to be optimized, $\left(s_{1(i,\max)}, s_{2(i,\max)}, \ldots, s_{12(i,\max)}\right)$ represent Mom and $\left(\overline{s}_{1(i,mean)}, \overline{s}_{2(i,mean)}, \ldots, \overline{s}_{12(i,mean)}\right)$ represent Dad respectively for object variables, α_k , $k = 1,2,3,\ldots,12$, is selected from URN [0, 1] and α_k is sampled anew for each selected parameter of the individuals.

(3) The Mutation phase provides random excursions into new location of search space. For this phase dynamic Time Variant Mutation (TVM) operator is used to improve fine local tuning and to ensure fast convergence. TVM operation for offspring is defined as:

$$\zeta_1'^t = \left(\xi'_{S1}, \xi'_{S2}, \xi'_{S3}, \ldots, \xi'_{S12}\right) \tag{27}$$

$$\zeta_1'^t = \big(\xi_{S1} + \sigma(1)\cdot N_1(0,1),\ \xi_{S2} + \sigma(1)\cdot N_2(0,1), \ldots, \xi_{S11} + \sigma(1)\cdot N_{11}(0,1),\ \xi_{S12} + \sigma(1)\cdot N_{12}(0,1)\big) \tag{28}$$

where $\xi'_{S1}, \xi'_{S2}, \xi'_{S3}, \ldots, \xi'_{S12}$ represent the new offspring, $N_k(.,.)$ indicates the Gaussian random value with zero–mean and unity variance, and is sampled anew for each value of the index *k*. And $\sigma(t)$ is the time-variant mutation step generating function at the generation t, which is defined by

$$\sigma(t) = [1 - r^{(1-t/T)^{\gamma}}] \tag{29}$$

where r is selected from URN [0, 1], T is the maximal generation number, γ is a real-valued parameter determining the degree of dependency on the generations.

Apparently TVM generates high value at initials stages and low value at final stages. This might violate the domain of selected parameters and in such case that offspring is left without mutation as explained in figure 5.

(4) After mutation operation each offspring is evaluated by its fitness function. The fitness function is developed to improve tracking performance and minimize control energy to reduce chattering effect. The fitness function is defined as:

$$J = w_1 \sum_{t=0}^{T_0} |e(t)| + w_2 \sum_{t=0}^{T_0} |u(t)| \tag{30}$$

where w_1 is the weighting factor to improve tracking performance, w_2 is the weighting factor to minimize control effort, T_0 is the total time for which the function is evaluated, $|e(t)|$ is the absolute error and $|u(t)|$ is the absolute control output. The lower the value of J is, the better the performance.

(5) In the alternate generation phase parent μ_j^{t-1} and children μ_j^t are combined and ordered according to their fitness function. Best μ_j individuals are selected for the next generation.

6. Results and Discussion

The proposed controller is applied to nonlinear electro hydraulic servo system whose parameters can be found in our other research work [17, 23]. Fine tracking performance with reduced chattering amplitude is the key performance indicator of our aspiration. Traditional SMC is robust to system uncertainty, but it can lead to undesirable chattering effect as described in figure 2. Integration of fuzzy control to conventional SMC result in better tracking performance with reduced chattering amplitude as is described in figure 4. However, the performance is not content with the defined objectives because control parameters are acquired with manual tuning. To cope with this problem controller parameters are optimized with NEA. The optimization curve is illustrated in figure 9 and optimized parameters are given in table 3.

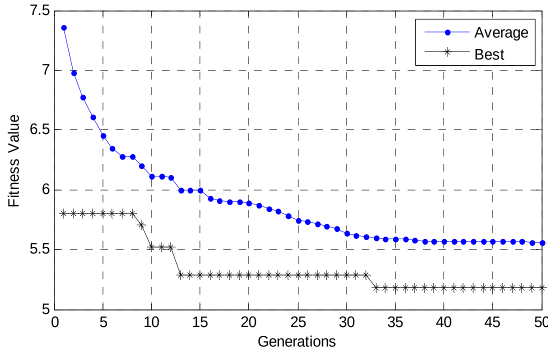

Figure 9. Optimization curve for NEA.

Table 3. Optimized parameters of FSMC.

Optimized value of object variables for optimization of Fuzzy Sliding Mode			
Fuzzy	MFs Distribution	Scaling Factors	Weighting Factor
	S_1=0.1607 S_2=0.2194 S_3 =0.3948 S_4 =0.5914 S_5 =0.1037	Se=477.0348 Sce=58.9235 Si =2786.5	w_f=0.8404
SMC	Lambda	Boundary layer	Weighting factor
	λ =95	ϕ=0.3153	w_{sw}=0.3693

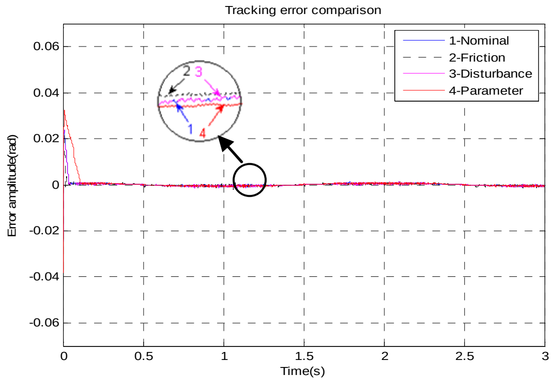

Figure 10. Tracking performance comparison for optimized FSMC.

To validate the effectiveness of proposed controller and thus the effectiveness of optimization, performance is evaluated under different disturbances. A meticulous comparison of tracking performance is shown in figure 10 and is explained as:

Nominal Conditions: Under these conditions the performance of proposed controller is evaluated without any disturbance effect as shown by curve 1.

Increased Friction Effect: Under these conditions friction effect is increased to twice to validate the effectiveness of controller against nonlinearities. Very small variation is observed as shown by curve 2.

Disturbance Effect: Under these conditions a constant disturbance torque of 100 Nm is applied at t=1 s and then this disturbance torque is increased to 150 Nm at t=2 s. The purpose of this is to evaluate the effectiveness against the sudden impact of any disturbance torque. The performance under disturbance is shown by curve 3.

Parameters variation Effect: The objective of this is to ensure the effectiveness under parametric uncertainties. Different parameters variations are studied. However, in figure 10 only supply pressure variation is given due to its prominent effect as shown by curve 4. Different parameter variations can be described as:

a. Supply pressure is changed from $1.25\times10^7 N/m^2$ to $1\times10^7 N/m^2$.
b. Bulk modulus is decreased from $6.86\times10^8 N/m^2$ to $6\times10^8 N/m^2$.
c. Bulk modulus is increased to $7.5\times10^8 N/m^2$.

Simulation results presented in figure 10 confirm the effectiveness and robustness of proposed controller under all disturbance effects.

To further elaborate and validate the effectiveness of proposed controller performance comparison is made among SMC, FSMC and optimized FSMC (OFSMC) under the effect of increased friction. Simulation results are given in figure 11, in which curve 1 is the tracking error with SMC, curve 2 shows the one with FSMC and curve 3 expresses the one with OFSMC. Simulation results authenticate the effectiveness of proposed technique.

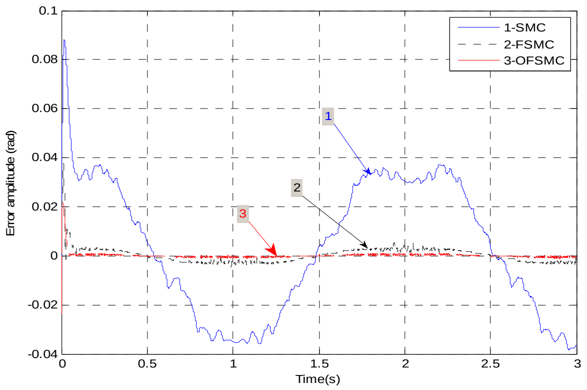

Figure 11. Comparison of tracking error with different controller under friction effect.

In order to validate the effectives, the experiment of EHSS is carried out based on SMC and OFSMC. Experimental set up for EHSS consists of hydraulic power supply, Moog servo valve, hydraulic motor and encoder as shown in figure 12.

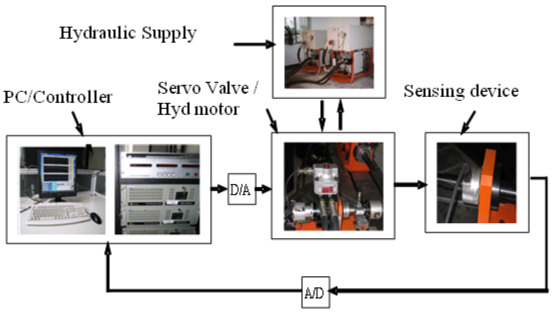

Figure 12. Experimental setup of EHSS.

Experimental results in figure 13 indicate that OFSMC not only reduce chattering effect but also improve the performance synchronously. In addition, it also offers robustness against parametric variations and disturbances.

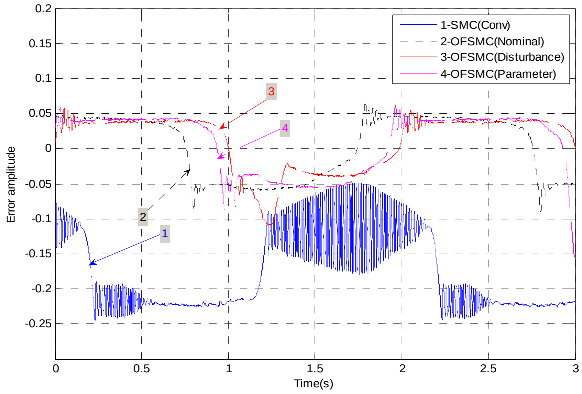

Figure 13. Comparison of tracking error under different effects.

Consequently, it might be concluded that the proposed techniques not only reduce the chattering amplitude but also improve the tracking performance.

7. Conclusions

In this contribution, fuzzy sliding mode control is introduced and evolutionary simultaneous tuning of control parameters is employed with objectives of reducing the chattering amplitude and improving the tracking performance. Novel evolutionary algorithm (NEA) is applied for simultaneous optimization process due to its computational efficiency and reliability. Chattering reduction issue is further improved by introducing the weighting factors estimation technique. In this technique, weighting factors for each control term are estimated with the objective to provide the control action according to desired response. The integrated weighted control action not only reduces the chattering amplitude but also improves the tracking performance. The proposed techniques are applied to nonlinear electro-hydraulic servo system. Performance analysis is made under different disturbance effects to validate the effectiveness. The simulation and experimental results prove that the proposed controller has the potential to reduce chattering amplitude up to significant level and offer precise tracking performance. Further, simulations and experiments also validate the effectiveness and robustness of proposed controller under unknown modeling errors, parametric uncertainties and external disturbances.

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