Design Model-free Fuzzy Sliding Mode Control: Applied to Internal Combustion Engine

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Abstract

Modeling and control of engine systems are vital due to wide range of their applications. As it is obvious stability is the minimum requirement in any control system, however the proof of stability is not trivial especially in the case of nonlinear systems. One of the most active research areas in field of internal combustion engine (IC engine) is control of the fuel ratio. The strategies for control of engines are classified into two main groups: classical and non-classical methods, where the classical methods used the conventional control theory and non-classical methods used the artificial intelligence theory such as fuzzy logic, neural networks and/or neurofuzzy. One of the best nonlinear robust controllers which can be used in uncertainty nonlinear systems is sliding mode controller (SMC). Chattering phenomenon is the main challenge in this controller. Fuzzy logic and neuro control have been applied successfully in many applications. Therefore stable control of an internal combustion engine is challenging because it has uncertain dynamic parameters. This research presents design a fuzzy sliding mode control with improved in sliding mode algorithm which offers a model-free sliding mode methodology. The fuzzy sliding mode controller is designed as a 49 rules Mamdani's error-based fuzzy sliding-like equivalent part instead of nonlinear dynamic equation of equivalent part. Various performance indices like the minimum error, trajectory, disturbance rejection, and chattering control are used for comparison.

Keywords: Internal Combustion Engine, Sliding Mode Controller, Chattering Phenomenon, Fuzzy Sliding Mode Controller, Minimum Error, Trajectory, Disturbance Rejection, and Chattering Control.

1. INTRODUCTION

The internal combustion (IC) engine is designed to produce power from the energy that is contained in its fuel. More specifically, its fuel contains chemical energy and together with air, this mixture is burned to output mechanical power. There are various types of fuels that can be used in IC engines which include petroleum, diesel, bio-fuels, and hydrogen [1]. The output power produced by an IC engine results from the fuel, that it uses, and also its mechanical parts [2]. Modeling of an entire IC engine is a very important and complicated process because engines are nonlinear, multi inputs-multi outputs and time variant. One purpose of accurate modeling is to save development costs of real engines and minimizing the risks of damaging an engine when validating controller designs. Nevertheless, developing a small model, for specific controller design purposes, can be done and then validated on a larger, more complicated model. [3], [4], [5].

Controller design is the main part in IC engines as well as the major objectives is stability and robustness. One of the significant challenges in control algorithms is a linear behavior controller design for nonlinear systems. When system works with various parameters and hard nonlinearities this technique is very useful in order to be implemented easily but it has some limitations such as working near the system operating point[2]. Some of IC engines which work in industrial processes are controlled by linear PID controllers, but the design of linear controller for IC engines is extremely difficult because they are nonlinear, uncertainty, and MIMO[1, 6]. To reduce above challenges the nonlinear robust controllers is used to systems control. One of the best nonlinear robust controller that can used in uncertainty nonlinear systems (e.g., IC engines), is sliding mode controller. But, SMC also has attachment to dynamic equation using equivalent control, so used fuzzy logic system instead equivalent control (e.g., proposed fuzzy sliding mode controller). To have the best solution, this paper focuses on self tuning robust controller (e.g., self tuning fuzzy sliding mode controller) [6], [7].

One of the powerful nonlinear robust controllers is sliding mode controller (SMC), although this controller has analyzed by many researchers recently but the first proposed was in the 1950 [7].This controller is used in wide range areas such as in robotics, in control process, in aerospace applications, and in IC engines because it has an acceptable control performance and solve some main challenging topics in control such as resistivity to the external disturbance [18-24]. Even though, this controller is used in wide range areas but, pure sliding mode controller has the following disadvantages: Firstly, chattering problem; which caused the high frequency oscillation in the controllers output. Secondly, equivalent dynamic formulation; calculate the equivalent control formulation is difficult because it depends on the dynamic equation [8, 9]. The classical sliding mode controller is classified into two main parts: discontinuous (hitting) controller which is based on discontinuous switching function and equivalent controller which is based on dynamic equations of IC engine.

On the other hand, after the invention of fuzzy logic theory in 1965, this theory was used in wide range applications that fuzzy logic controller (FLC) is one of the most important applications in fuzzy logic theory because the controller has been used for nonlinear and uncertain (e.g., robot manipulator) systems controlling. Conversely pure FLC works in many areas, it cannot guarantee the basic requirement of stability and acceptable performance[10, 11].

Although both SMC and FLC have been applied successfully in many applications but they also have some limitations. The boundary layer method is used to reduce or eliminate the chattering and proposed method focuses on substitution error-base fuzzy logic system instead of dynamic equivalent equation to implement easily and avoid mathematical model base controller [20-24]. To reduce the effect of uncertainty in proposed method, self tuning method is applied in error-base fuzzy sliding mode controller [18-24] in IC engine. This paper is organized as follows: In section 2, main subject of engine operating cycle are presented. Detail of modelling of fuel ratio in IC engine is presented in section 3. Detail of classical sliding mode controller is presented in section 4. In section 5, the main subject of proposed fuzzy sliding mode controller is presented. In section 6, the simulation result is presented and finally in section 7, the conclusion is presented.

2. ENGINE OPERATING CYCLE

In an internal combustion engine, a piston moves up and down in a cylinder and power is transferred through a connecting rod to a crank shaft. The continual motion of the piston and rotation of the crank shaft as air and fuel enter and exit the cylinder through the intake and exhaust valves is known as an engine cycle. The first and most significant engine among all internal combustion engines is the Otto engine, which was developed by Nicolaus A. Otto in 1876 (Figure 1). In his engine, Otto created a unique engine cycle that consisted of four piston strokes. These strokes are:
1. Intake stroke
2. Compression stroke
3. Expansion stroke
4. Exhaust stroke

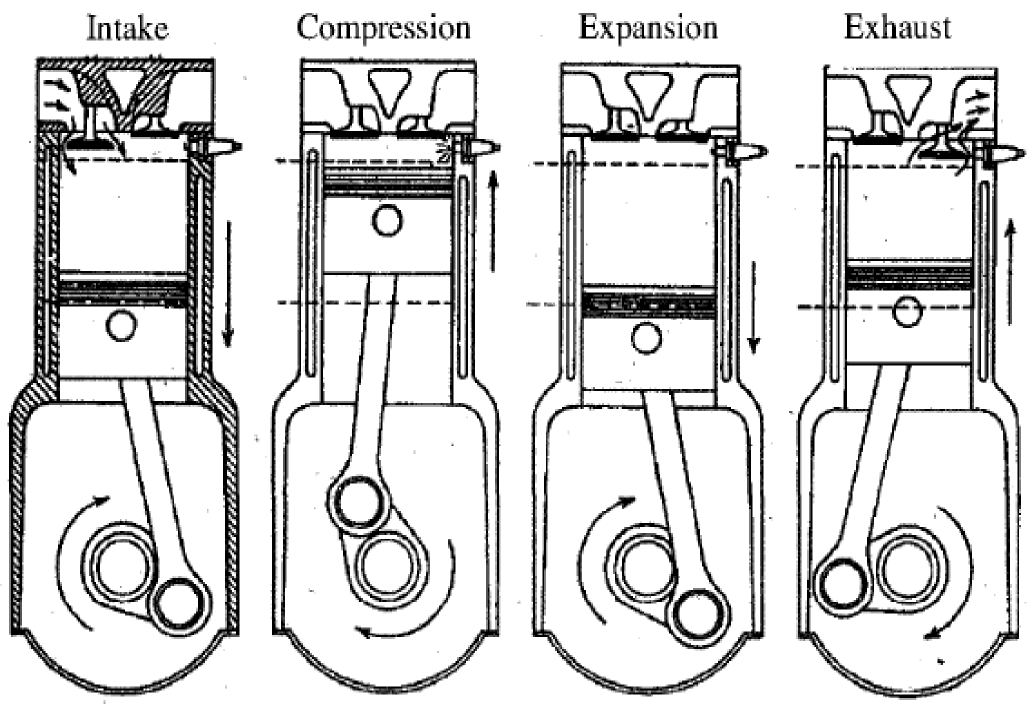


FIGURE 1: The Four Stroke Engine Cycle [1]

During the intake stroke, the piston begins at top-dead-center (TDC) and ends at bottomdead-center (BDC). An air and gasoline mixture enters the cylinder through the intake valve and in some cases this valve opens slightly before the intake stroke begins to allow more air-fuel mixture into the cylinder. During the compression stroke, the intake and exhaust valves are closed and the mixture is compressed to a very small fraction of its initial volume. The compressed mixture is then ignited by a spark causing the pressure to rise very rapidly [12].

During the expansion stroke, the piston begins at (TDC). Due to the high pressure and temperature gases in the cylinder, the piston is now pushed down, causing the crank to rotate. As the piston approaches (BDC) the exhaust valve opens. During the exhaust stroke, the burned gases exit the cylinder due to the high cylinder pressure and low exhaust pressure and also due to the piston moving up towards TDC. The cycle starts again after the exhaust valve closes.

A complete engine cycle is divided into 720 crank angle degrees, where the crank angle is between the piston connecting rod at TDC and the connecting rod away from TDC. This means that the piston will move up and down in the cylinder two times during one complete engine cycle. Since there are two revolutions in one engine cycle, time duration (in seconds) of one engine cycle can be found given the rotations-per-minute (RPM). For example, at 1500 RPM, an engine cycle lasts 80 milliseconds (ms) and at 3000 RPM an engine cycle lasts 40 ms [13].

3. MODELLING OF ENGINE

In developing a valid engine model, the concept of the combustion process, abnormal combustion, and cylinder pressure must be understood. The combustion process is relatively simple and it begins with fuel and air being mixed together in the intake manifold and cylinder. This air-fuel mixture is trapped inside cylinder after the intake valve(s) is closed and then gets compressed [13].

When the air-fuel mixture is compressed it causes the pressure and temperature to increase inside the cylinder. Unlike normal combustion, the cylinder pressure and temperature can rise so rapidly that it can spontaneously ignite the air-fuel mixture causing high frequency cylinder pressure oscillations. These oscillations cause the metal cylinders to produce sharp noises called knock, which it caused to abnormal combustion.

The pressure in the cylinder is a very important physical parameter that can be analyzed from the combustion process. After the flame is developed, the cylinder pressure steadily rises, reaches a maximum point after TDC, and finally decreases during the expansion stroke when the cylinder volume increases. Since cylinder pressure is very important to the combustion event and the engine cycle in spark ignition engines, the development of a model that produces the cylinder pressure for each crank angle degree is necessary. A cylinder pressure model that calculates the total cylinder pressure over 720 crank angle degrees was created based upon the following formulation [12-13], [17]:

$$\boldsymbol{P_{cyl}(\theta) = P_m(\theta) + P_{net}(\theta)} \tag{1}$$

where $P_{cyl}(\theta)$ is pressure in cylinder, $P_m(\theta)$ is Wiebe function, and $P_{net}(\theta)$ is motoring pressure of a cylinder. Air fuel ratio is the mass ratio of air and fuel trapped inside the cylinder before combustion starts. Mathematically it is the mass of the air divided by the mass of the fuel as shown in the equation below:

$$\boldsymbol{Air\ to\ Fuel = \frac{\dot{m}_{air}}{\dot{m}_{fuel}}} \tag{2}$$

If the ratio is too high or too low, it can be adjusted by adding or reducing the amount of fuel per engine cycle that is injected into the cylinder. The fuel ratio can be used to determine which fuel system should have a larger impact on how much fuel is injected into the cylinder. Since a direct fuel injector has immediate injection of its fuel with significant charge cooling effect, it can have a quicker response to the desired amount of fuel that is needed by an engine [17].

4. CLASSICAL SLIDING MODE CONTROL

Sliding mode controller (SMC) is a powerful nonlinear controller which has been analyzed by many researchers especially in recent years. This theory was first proposed in the early 1950 by Emelyanov and several co-workers and has been extensively developed since then with the invention of high speed control devices[15-16].
A time-varying sliding surface $\boldsymbol{s(x,t)}$ is given by the following equation [18-24]:

$$\boldsymbol{S(x,t) = (\frac{d}{dt} + \lambda)^{n-1}\,\tilde{x} = 0} \tag{3}$$

where λ is the constant and it is positive. A simple solution to get the sliding condition when the dynamic parameters have uncertainty is the switching control law:

$$U_{dis} = \hat{U} - K(\vec{x},t).sgn(s) \tag{4}$$

Where the function of $sgn(S)$ defined as;

$$sgn(s) = \begin{cases} 1 & s > 0 \\ -1 & s < 0 \\ 0 & s = 0 \end{cases} \tag{5}$$

and the $K(\vec{x},t)$ is the positive constant. To reduce or eliminate the chattering it is used the boundary layer method; in boundary layer method the basic idea is replace the discontinuous method by saturation (linear) method with small neighborhood of the switching surface. This replace is caused to increase the error performance [20-24].

$$B(t) = \{x, |S(t)| \le \emptyset\}; \emptyset > 0 \tag{6}$$

Where $\emptyset$ is the boundary layer thickness. Therefore, to have a smote control law, the saturation function $Sat(S/_{\emptyset})$ added to the control law:

$$U = K(\vec{x},t).Sat\left(S/_{\emptyset}\right) \tag{7}$$

Where $Sat\left(S/_{\emptyset}\right)$ can be defined as

$$sat\left(S/_{\emptyset}\right) = \begin{cases} 1 & (S/_{\emptyset} > 1) \\ -1 & \left(S/_{\emptyset} < 1\right) \\ S/_{\emptyset} & (-1 < S/_{\emptyset} < 1) \end{cases} \tag{8}$$

Based on above discussion, the control law for a multi degrees of freedom robot manipulator is written as [18-24]:

$$U = U_{eq} + U_r \tag{9}$$

Where, the model-based component U_{eq} is compensated the nominal dynamics of systems. Therefore U_{eq} can calculate as follows:

$$U_{eq} = \left[M^{-1}\left(P_m(\theta) + P_{net}(\theta)\right) + \dot{S}\right]M \tag{10}$$

Where

$$M^{-1} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}^{-1} \quad M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}$$

5. DESIGN PROPOSED FUZZY SLIDING MODE CONTROLLER

The most important objective in fuzzy sliding mode controller (FSMC) is design sliding mode control combined to fuzzy logic systems to resolve most important problems in pure sliding mode controller. This research focuses on resolve the equivalent nonlinear dynamic sliding mode controller by use a new method. To compensate the nonlinearity of dynamic equivalent control some researchers is used model base fuzzy controller instead of classical equivalent controller. This technique was employed to obtain the desired control behavior with a number of information about dynamic model of system and a fuzzy switching control was applied to reinforce system performance. In contrast proposed methodology is used error based fuzzy instead of classical equivalent dynamic to have an acceptable performance and easy to implementation. According to the new method model free controller design is the basis of research so it's found that there is a big difference between this new method with the old one that was based on equivalent in order to undefined dynamic models compensation.

The most important objects in fuzzy sliding mode controller (FSMC) are applied fuzzy logic controller in sliding mode controller to solve equivalent problems in classical sliding mode controller. In proposed fuzzy sliding mode controller error based Mamdani's fuzzy inference system has considered with two inputs, one output and totally 49 rules instead of the dynamic equivalent part.

For both SMC and FSMC applications the system performance is sensitive to the sliding surface slope(λ). For instance, if large value of λ is chosen the response is very fast but the system is very unstable and conversely, if small value of λ is considered the response of system is very slow but the system is very stable. Therefore, calculation the optimum value of λ is the other important challenge works. A block diagram for proposed fuzzy sliding mode controller is shown in Figure 2. In this method a model free Mamdani's fuzzy inference system has considered based on fuzzy logic controller instead of equivalent control. In FSMC the equation can be written as;

$$U = U_{eq_{fuzzy}} + U_r \qquad \textbf{(11)}$$

As mentioned as Figure 2, as a summary the design of fuzzy like equivalent part based on Mamdani's fuzzy inference method has four steps , namely, fuzzification, fuzzy rule base and rule evaluation, aggregation of the rule output (fuzzy inference system), and deffuzzification.

Fuzzification: the first step in fuzzification is determine inputs and outputs which, it has two inputs $(e, \dot{e})$ and one output (U_{fuzzy}). The inputs are error (e) which measures the difference between desired and actual inputs, and the change of error $(\dot{e})$ which measures the difference between desired and actual velocity and output is fuzzy equivalent estimator. The second step is chosen an appropriate membership function for inputs and output which, for simplicity in implementation and also to have an acceptable performance the researcher is selected the triangular membership function. The third step is chosen the correct labels for each fuzzy set which, in this research namely as linguistic variable. The linguistic variables for error (e) are; Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Big (PB), and it is quantized in to thirteen levels represented by: -1, -0.83, -0.66, -0.5, -0.33, -0.16, 0, 0.16, 0.33, 0.5, 0.66, 0.83, 1 the linguistic variables for change of error $(\dot{e})$ are; Fast Left (FL), Medium Left (ML), Slow Left (SL),Zero (Z), Slow Right (SR), Medium Right (MR), Fast Right (FR), and it is quantized in to thirteen levels represented by: -6, -5, -0.4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6, and the linguistic variables to find the output are; Large Left (LL), Medium Left (ML), Small Left (SL), Zero (Z), Small Right (SR), Medium Right (MR), Large Right (LR) and it is quantized in to thirteen levels represented by: -6, -5, -0.4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6.

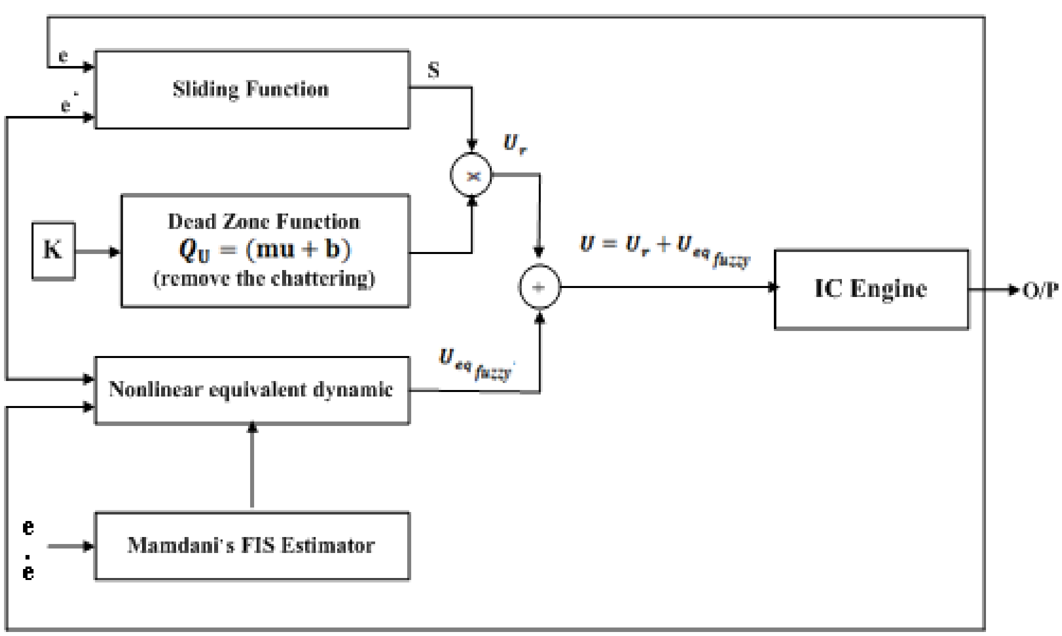


FIGURE 2: Block diagram of proposed fuzzy sliding mode controller

Fuzzy Rule Base and Rule Evaluation: the first step in rule base and evaluation is provide a least structured method to derive the fuzzy rule base which, expert experience and control engineering knowledge is used because this method is the least structure of the other one and the researcher derivation the fuzzy rule base from the knowledge of system operate and/or the classical controller. Design the rule base of fuzzy inference system can play important role to design the best performance of fuzzy sliding mode controller, that to calculate the fuzzy rule base the researcher is used to heuristic method which, it is based on the behavior of the control of IC engine suppose that two fuzzy rules in this controller are;

F.R^1: *IF e is NB and $\dot{e}$ is FL, THEN U is LL.* **(12)**

F.R^2: *IF e is PS and $\dot{e}$ is FL THEN U is ML*

The complete rule base for this controller is shown in Table 1. Rule evaluation focuses on operation in the antecedent of the fuzzy rules in fuzzy sliding mode controller. This part is used AND/OR fuzzy operation in antecedent part which AND operation is used.

$\dot{e}$ \ e	NB	NM	NS	ZE	PS	PM	PB
NB	PB	NB	NB	NM	NS	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	PS	PS	PM	PB	PB	NB	ZE

TABLE 1: Modified fuzzy rule base table

Aggregation of the Rule Output (Fuzzy inference): Max-Min aggregation is used to this work which the calculation is defined as belows.

$$\mu_U(x_k,y_k,U) = \mu_{\cup_{i=1}^{r} FR^i}(x_k,y_k,U) = max\left\{min_{i=1}^{r}\left[\mu_{R_{pq}}(x_k,y_k),\mu_{p_m}(U)\right]\right\} \quad (13)$$

Deffuzzification: The last step to design fuzzy inference in our fuzzy sliding mode controller is defuzzification. This part is used to transform fuzzy set to crisp set, therefore the input for defuzzification is the aggregate output and the output of it is a crisp number. In this design the Center of gravity method (COG) is used and calculated by the equation 14.

$$COG(x_k,y_k) = \frac{\sum_i U_i \sum_{j=1}^{r} \cdot \mu_u(x_k,y_k,U_i)}{\sum_i \sum_{j=1}^{r} \cdot \mu_u(x_k,y_k,U_i)} \quad (14)$$

Table 2 is shown the lookup table in fuzzy sliding mode controller which is computed by COG deffuzzification method. These output values were obtained from trial and error after some manual adjustment to reach the best performance in fuzzy sliding mode controller. Table 2 has 169 cells to shows the fuzzy like equivalent part behavior. For instance if $e = 0$ and $\dot{e} = 0$ then the output or $fuzzy\ like\ equivalent\ torque = 6$. By comparing between the COG deffuzzification and the equivalent part it found that this controller works well because it can be reducing the chattering and error with respect to eliminate the dynamic equation in equivalent part.

$\dot{e}$ → / e ↓	**Membership Function**												
	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
-1	-5	-5	-5	-5	-3	-2	-1	0	1	2	3	3	3
-0.83	-5	-5	-4	-3	-2	-1	-1	0	1	2	3	3	4
-0.66	-5	-5	-4	-3	-2	-1	0	1	1	2	3	4	5
-0.5	-5	-4	-3	-2	-1	-1	0	1	2	3	3	4	5
-0.33	-6	-5	-3	-2	-1	-1	0	1	2	3	3	4	5
-0.16	-6	-5	-3	-2	-1	-1	0	1	2	3	4	5	6
0	-5	-5	-4	-3	-2	-1	0	1	2	3	5	5	6
0.16	-5	-4	-3	-3	-2	-1	0	1	2	4	5	5	6
0.33	-4	-4	-3	-3	-1	0	0	2	3	4	5	5	6
0.5	-3	-3	-2	-2	0	0	0	2	3	4	5	6	6
0.66	-2	-1	-1	0	0	1	2	3	4	5	5	6	6
0.83	-1	0	0	1	1	2	2	3	4	5	6	6	6
1	0	1	2	2	2	3	4	4	5	5	5	6	6

TABLE 2: COG lookup table in fuzzy sliding mode controller: applied to IC engine

6. RESULTS

PD Matlab-based sliding mode controller (PD-SMC) and PD Matlab-based fuzzy sliding mode controller (PD-FSMC) were tested to Step response trajectory. The simulation was implemented in Matlab/Simulink environment. Fuel ratio trajectory, disturbance rejection and error are compared in these controllers. It is noted that, these systems are tested by band limited white noise with a predefined 40% of relative to the input signal amplitude which the sample time is equal to 0.1. This type of noise is used to external disturbance in continuous and hybrid systems.

6.1 Fuel Ratio Trajectory

Figure 3 shows the fuel ratio in PD-SMC and PD-FSMC without disturbance for Step trajectory. The best possible coefficients in Step PD-FSMC are; $K_p = K_v = 30,\ \emptyset = 0.1, and\ \lambda = 6$ as well as similarly in Step PD-SMC are; $K_p = K_v = 10,\ \emptyset = 0.1, and\ \lambda = 8.$

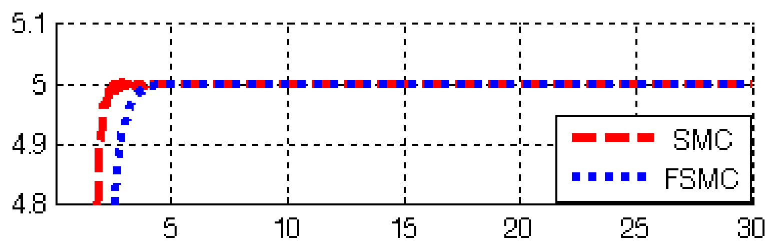


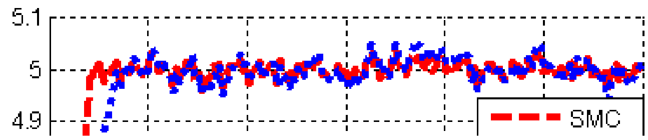
FIGURE 3: SMC Vs. FSMC: fuel ratio

By comparing step response, Figure 3, in PD-SMC and PD-FSMC, conversely the FSMC's overshoot **(0%)** is lower than SMC's **(1%)**, the SMC's rise time **(0.483 Sec)** is dramatically lower than FSMC's **(0.9 Sec)**; in addition the Settling time in FSMC **(Settling time=0.65 Sec)** is fairly lower than SMC **(Settling time=1.4 Sec)**.

6.2 Disturbance Rejection

Figure 4 is indicated the power disturbance removal in SMC and FSMC. As mentioned before, SMC is one of the most important robust nonlinear controllers. Besides a band limited white noise

FIGURE 4: SMC Vs. FSMC: fuel ratio with external disturbance



with predefined of 40% the power of input signal is applied to the step SMC and FSMC; it found slight oscillations in trajectory responses.

Among above graph, relating to step trajectory following with external disturbance, SMC and FSMC have slightly fluctuations. By comparing overshoot, rise time, and settling time; FSMC's overshoot **(0.9%)** is lower than SMC's **(1.1%)**, SMC's rise time **(0.48 sec)** is considerably lower than FSMC's **(0.9 sec)** and finally the Settling time in FSMC **(Settling time=0.65 Sec)** is quite lower than SMC **(Settling time=1.5 Sec)**.

6.3 Errors in the Model

Although SMC and FSMC have the same error rate (refer to Table.3), they have oscillation tracking which causes chattering phenomenon at the presence of disturbances. As it is obvious in Table.1 FSMC is a SMC which estimate the equivalent part so FSMC have acceptable performance with regard to SMC in presence of certain and uncertainty. Figure 5 is shown steady state and RMS error in SMC and FSMC in presence of external disturbance. However both of SMC and FSMC have slight oscillation but FSMC in presence of uncertainty has better response.

RMS Error Rate	**SMC**	**FSMC**
Without Noise	**1e-3**	**0.6e-3**
With Noise	**0.012**	**0.0012**

TABLE 3: RMS Error Rate of Presented controllers

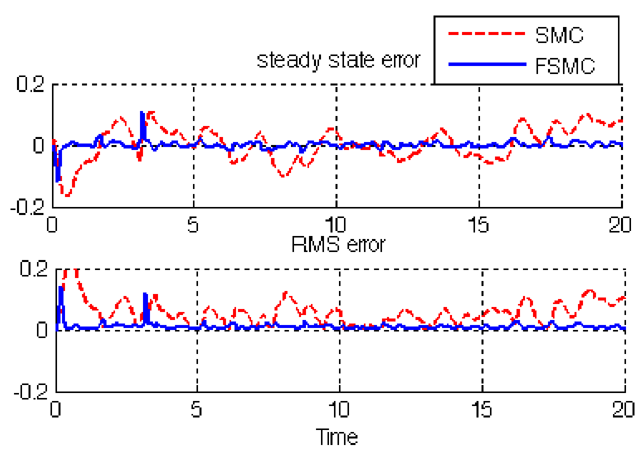


FIGURE 5: SMC Vs. FSMC: Steady state and RMS error in presence of external disturbance

In these methods if integration absolute error (IAE) is defined by (15), table 4 is shown comparison between these two methods.

$$IAE = \int_0^\infty |e(t)|\, dt \tag{15}$$

Method	FSMC	Traditional SMC
IAE	442.1	484.8

TABLE 4: Calculate IAE

7. CONCLUSION

Refer to the research, a fuzzy sliding mode control design and application to IC engine has proposed in order to design high performance nonlinear controller in the presence of uncertainties and external disturbances. Regarding to the positive points in sliding mode controller and fuzzy logic controller the output responses have improved. Fuzzy logic method by adding to the sliding mode controller has covered negative points. Obviously IC engine is nonlinear so this paper focuses on comparison between sliding mode controller and fuzzy sliding mode controller, to opt for better control method for the IC engine. Higher implementation quality of response and model free controller versus an acceptable performance in chattering, trajectory and error is reached by designing fuzzy sliding mode controller. This implementation considerably reduces the chattering phenomenon and error in the presence of uncertainties. As a result, this controller will be able to control a wide range of IC engine with a high sampling rates because its easy to implement versus high speed markets.

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