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Designing On-Line Tunable Gain Fuzzy Sliding Mode Controller Using Sliding Mode Fuzzy Algorithm: Applied to Internal Combustion Engine

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Abstract: This paper expands a fuzzy sliding mode based controller which sliding function is on-line tuned by sliding mode fuzzy algorithm. The main goal is to guarantee acceptable trajectories tracking between the internal combustion engine (IC engine) air to fuel ratio and the desired input. The fuzzy controller in proposed fuzzy sliding mode controller is based on Mamdani's fuzzy inference system (FIS) and it has one input and one output. The input represents the function between sliding function, error and the rate of error. The outputs represent fuel ratio, respectively. The sliding mode fuzzy methodology is on-line tune the sliding function based on self tuning methodology. The performance of the sliding mode fuzzy on-line tune fuzzy sliding mode controller (SFOFSMC) is validated through comparison with previously developed IC engine controller based on sliding mode control theory (SMC). Simulation results signify good performance of fuel ratio in presence of uncertainty and external disturbance.

Key words: Internal combustion engine · Sliding mode controller · Fuzzy sliding mode controller · Sliding mode fuzzy on-line tune fuzzy sliding mode controller

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 which can be used in IC engines namely; petroleum, diesel, bio-fuels, and hydrogen [1]. Modeling of an entire IC engine is a very important and complicated process because engines are nonlinear, multi inputs-multi outputs (MIMO) and time variant. There have been several engine controller designs over the past 40 years in which the goal is to improve the efficiency and exhaust emissions of the automotive engine. A key development in the evolution was the introduction of a closed loop fuel injection control algorithm by Rivard in the 1973 [2]. This strategy was followed by an innovative linear quadratic control method in 1980 by Cassidy [3] and an optimal control and Kalman filtering design by Powers [4]. Although the theoretical design of these controllers was valid, at that time it was not realistic to implement such complex designs. Therefore, the production of these designs did not exist and engine designers did adopt the methods. Due to the increased production of the microprocessor in the 1990's, it became practical to use these microprocessors in developing more complex control and estimation algorithms that could potentially be used in production automotive engines. Specific applications of A/F ratio control based on observer measurements in the intake manifold was developed by Benninger in 1991 [5]. Another approach was to base the observer on measurements of exhaust gases measured by the oxygen sensor and on the throttle position, which was researched by Onder [6]. These observer ideas used linear observer theory. Hedrick also used the measurements of the oxygen sensor to develop a nonlinear, sliding mode approach to control the A/F ratio [7]. All of the previous control strategies were applied to engines that used only port fuel injections, where fuel was injected in the intake

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manifold. The development of these control strategies for direct injection was not practical because the production of direct injection automobiles did not begin until the mid 1990's. Mitsubishi began to investigate combustion control technologies for direct injection engines in 1996 [8]. Furthermore, engines that used both port fuel and direct systems appeared a couple years ago, leading to the interest of developing the correspondin control strategies. Current production A/F ratio controllers use closed loop feedback and feed forward control to achieve the desired stoichio metric mixture. These controllers use measurements from the oxygen sensor to control the desired amount of fuel that should be injected over the next engine cycle and have been able to control the A/F very well.

Controller design is the main part in this paper as well as the major objectives in the controller design is stability and robustness. One of the significant challenges in control algorithms is design a linear behaviour controller 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[9]. Some of IC engines which work in industrial processes are controlled by linear controllers, but linear controller design for IC engines is extremely difficult [1, 6]. Sliding mode controller (SMC) is one of the influential nonlinear controllers in certain and uncertain systems which are used to solved stability and robustness [10]. The main reason for this popularity is the attractive properties which SMCs have, such as good control performance for nonlinear systems, applicability to MIMO systems and well-established design criteria for discrete-time systems. Conversely, this controller is used in different applications; sliding mode controller has subsequent drawbacks; firstly, there is the problem of chattering, which is the high-frequency oscillations of the controller output, brought about by the high-speed (ideally, at infinite frequency) switching necessary for the establishment of a sliding mode which in practical implementations, chattering is highly undesirable because it may excite unmodeled high-frequency plant dynamics, and this can result in unforeseen instabilities; secondly, an SMC is extremely vulnerable to measurement noise since the input depends on the sign of a measured variable that is very close to zero and thirdly the SMC may employ unnecessarily large control signals to overcome the parametric uncertainties and finally there exists appreciable difficulty in the calculation of what is known as the equivalent control [11-17]. In order to solve the chattering in the systems output, boundary layer method should be applied so beginning able to recommended model in the main motivation which in this method the basic idea is replace the discontinuous method by saturation (linear) method with small neighborhood of the switching surface [11-17]. Slotine and Sastry have introduced boundary layer method instead of discontinuous method to reduce the chattering [18]. Estimated uncertainty method is used in term of uncertainty estimator to compensation of the system uncertainties. It has been used to solve the chattering phenomenon and also nonlinear equivalent dynamic. The applications of artificial intelligence, neural networks and fuzzy logic on estimated uncertainty method have been reported in [19-22]. Wu *et al.* [23] have proposed a simple fuzzy estimator controller beside the discontinuous and equivalent control terms to reduce the chattering.

In recent years, artificial intelligence theory has been used in sliding mode control systems. Fuzzy logic controller (FLC) can be used to control nonlinear, uncertain and noisy systems. This method is free of some model-based techniques as in classical controllers. Fuzzy logic provides a method which is able to model a controller for nonlinear plant with a set of IF-THEN rules, or it can identify the control actions and describe them by using fuzzy rules. The applications of artificial intelligence, neural networks and fuzzy logic, on nonlinear systemcontrol have reported in [24-26]. Wai *et al.* [24-25] have proposed a fuzzy neural network (FNN) optimal control system to learn a nonlinear function in the optimal control law. This controller is divided into three main groups: arterial intelligence controller (fuzzy neural network) which it is used to compensate the system's nonlinearity and improves by adaptive method, robust controller to reduce the error and optimal controller which is the main part of this controller.

Research on applied fuzzy logic methodology in sliding mode controller (FSMC) to reduce or eliminate the high frequency oscillation (chattering), to compensate the unknown system dynamics and also to adjust the linear sliding surface slope in pure sliding mode controller considerably improves the robot manipulator control process [27-28]. H.Temeltas [29] has proposed fuzzy adaption techniques for SMC to achieve robust tracking of nonlinear systems and solves the chattering problem. Conversely system's performance is better than sliding mode controller; it is depended on nonlinear dynamic equation. Investigation on applied sliding mode methodology in fuzzy logic controller (SMFC) to reduce the fuzzy rules and refine the stability of close loop system in fuzzy logic controller has grown specially in recent years as the nonlinear system control [30-33]. Lhee *et al.* [32]have presented a fuzzy logic controller based on sliding mode controller to more formalize and boundary layer thickness.

In various dynamic parameters systems (e.g., IC engine) which need to be training, on-line tunable gain control methodology is used. In this research in order to solve disturbance rejection and uncertainty dynamic parameter, on-line tunable method is applied to artificial sliding mode controller. F Y Hsu *et al.* [34]have presented adaptive fuzzy sliding mode control which can update fuzzy rules to compensate nonlinear parameters and guarantee the stability robot manipulator controller. This paper is organized as follows: In section 2, main subject of engine operating cycle and detail dynamic formulation of modelling in IC engine are presented. Detail of proposed sliding mode fuzzy algorithm on-line fuzzy sliding mode controller is presented in section 3. In section 4, the simulation result is presented and finally in section 5, the conclusion is presented.

Application

Internal Combustion Engine Dynamic Formulation: 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 [35]. 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 [35-37]:

$$P_{cyl}(\theta) = P_m(\theta) + p_{net}(\theta) \quad (1)$$

where $P_{cul}(\theta)$ 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:

$$Air\,to\,Fuel = \frac{\dot{m}_{air}}{\dot{m}_{fuel}} \quad (2)$$

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 [37].

Design Proposed Sliding Mode Fuzzy On-line Tune Fuzzy Sliding Mode Controller: 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[11-17].

A time-varying sliding surface $s(x,t)$ is given by the following equation:

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

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:

$$U_{rdis} = \tilde{U} - K(\vec{x},t).\,\mathrm{sgn}(s) \quad (4)$$

Where the switching function of $sgn(S)$ defined as and the $K(\vec{x},t)$ is the positive constant;

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

To reduce or eliminate the chattering it is used the dead zone boundary layer method; in this 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.

$$B(t) = \{x, | S(t) | \leq \varnothing\} \varnothing > 0 \quad (6)$$

Where ⌀ is the boundary layer thickness. Therefore, to have a smote control law, the saturation function $Sat\left(S/\varnothing\right) = .(\text{mu+b})\left(S/\varnothing\right)$ added to the control law [12-14]:

$$U_{rsat} = K(\vec{x}, t).(\text{mu+b})\left(S/\varnothing\right) \quad (7)$$

Where $Sat\left(S/\varnothing\right)$ can be defined as

$$Sat\left(S/\varnothing\right) = \begin{cases} 1 & \left(s/\varnothing > 1\right) \\ -1 & \left(s/\varnothing < 1\right) \\ s/\varnothing & \left(-1 < s/\varnothing < 1\right) \end{cases} \quad (8)$$

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

$$U = U_{eq} + U_r \quad (9)$$

Where, the model-based component $\hat{\tau}_{eq}$ is compensated the nominal dynamics of systems. Therefore $\hat{\tau}_{eq}$ can calculate as follows:

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

Where

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

The fuzzy system can be defined as below

$$f(x) = U_{fuzzy} = \sum_{l=1}^{M} \theta^T \iota(x) = \psi(S) \quad (11)$$

where

$$\theta = \left(\theta^1, \theta^2, \theta^3, \ldots.\theta^M\right)^T, \zeta(x) = \Psi\left(\zeta^1(x), \zeta^2(x), \zeta^3(x), \ldots.\zeta^M(x)\right)^T$$

$$\iota^1(x) = \frac{\sum_i \mu_{(xi)xi}}{\sum_i \mu_{(xi)}} \quad (12)$$

where $\theta = \left(\theta^1, \theta^2, \theta^3, \ldots.\theta^M\right)$ is adjustable parameter in (8) and $\mu_{(xi)}$ is membership function. error base fuzzy controller can be defined as

$$U_{fuzzy} = \psi(S) \quad (13)$$

The fuzzy division can be reached the best state when $S.\dot{S} < 0$ and the error is minimum by the following formulation

$$\theta^* = \text{argmin}\left[S\,\text{up}_{x \in U} \mid \sum_{l=1}^{M} \theta^T \zeta(x) - U_{equ} \mid\right] \quad (14)$$

Where θ^* is the minimum error, $S\,\text{up}_{x \in U} \mid \sum_{l=1}^{M} \theta^T \zeta(x) - \tau_{equ} \mid$ is the minimum approximation error. suppose K_j is defined as follows

$$K_j = \frac{\sum_{l=1}^{M} \theta_j^l \left[\mu_A(S_j)\right]}{\sum_{l=1}^{M} \left[\mu_A(S_j)\right]} = \theta_j^T \zeta_j(S_j) \quad (15)$$

Where $\zeta_j(S_j) = \left[\zeta_j^1(S_j), \zeta_j^2(S_j), \zeta_j^3(S_j), \ldots.\zeta_j^M(S_j)\right]^T$

$$\zeta_j^1(S_j) = \frac{\mu(A)_j^l(S_j)}{\sum_i \mu(A)_j^l(S_j)} \quad (16)$$

where the γ_{sj} is the positive constant.

According to the nonlinear dynamic equivalent formulation of robot manipulator the nonlinear equivalent part is estimated by (11)

$$\left[M^{-1}\left(P_m(\theta) + P_{net}(\theta) + \dot{S}\right)\right]M = \sum_{l=1}^{M} \theta^T \zeta(x) - \lambda S - K \quad (17)$$

Based on (9) the formulation of proposed fuzzy sliding mode controller can be written as;

$$U = U_{eqfuzzy} + U_r \quad (18)$$

Where

$$U_{eqfuzzy} = \left[M^{-1}\left(P_m(\theta) + P_{net}(\theta) + \dot{S}\right)\right]M = \sum_{l=1}^{M} \theta^T \zeta(x) + K$$

Figure 1 is shown the proposed fuzzy sliding mode controller.

However proposed FSMC has satisfactory performance but calculate the sliding surface slope by try and error or experience knowledge is very difficult, particularly when system has uncertainties; sliding mode fuzzy self tuning sliding function fuzzy sliding mode controller is recommended.

$$U_{SF} = \Psi\left(K.(\text{mu+b}).\left(S/\varnothing\right)\right) \quad (19)$$

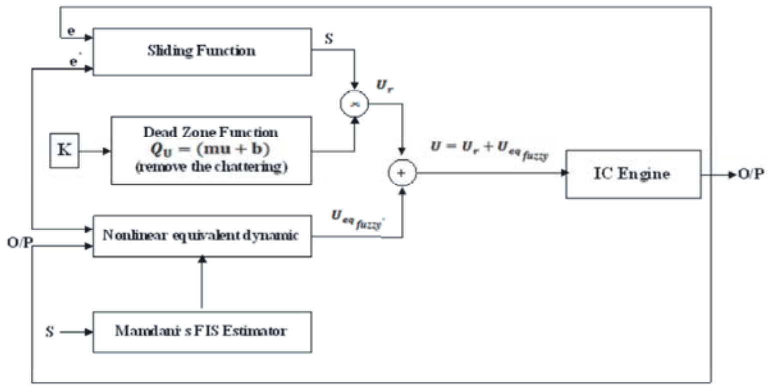

Fig. 1: Proposed fuzzy sliding mode algorithm: applied to IC engine

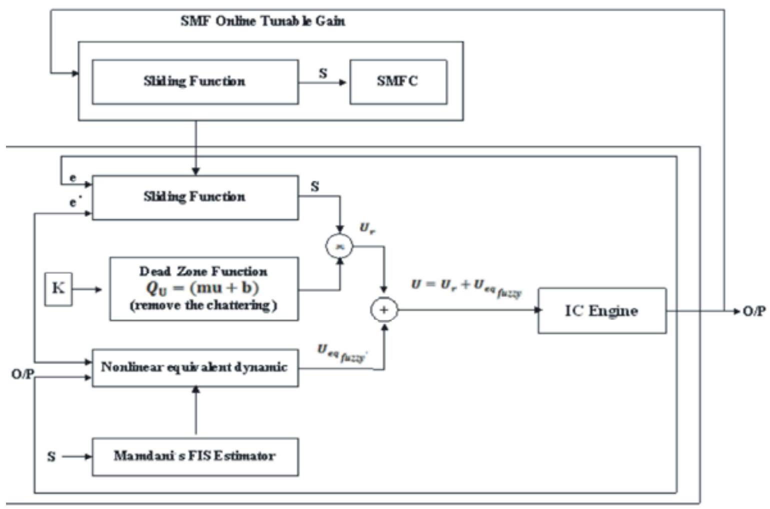

Fig. 2: Proposed on line sliding fuzzy tune FSMC algorithm: applied to IC engine

Where U_{SF} is sliding mode fuzzy output function. The adaption low is defined as

$$\theta_j = \gamma_{sj} S_j \zeta_j \left(S_j\right) \tag{20}$$

where the γ_{Sj} is the positive constant and $\zeta_j\left(S_j\right) = \left[\zeta_j^1\left(S_j\right), \zeta_j^2\left(S_j\right), \zeta_j^3\left(S_j\right), ...\zeta_j^M\left(S_j\right)\right]^T$

$$\zeta_j^1\left(S_j\right) = \frac{\mu(A)_j^l\left(S_j\right)}{\sum_i \mu(A)_j^l\left(S_j\right)} \tag{21}$$

As a result SFOFSMC is very stable with a good performance. Figure 2 is shown the block diagram of proposed SFOFSMC.

RESULTS

To validation of this work it is used IC engine and implements proposed SFOFSMC and SMC in this IC engine. The simulation was implemented in Matlab/Simulink environment. Fuel ratio, torque performance, disturbance rejection, steady state error and RMS 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. This type of noise is used to external disturbance in continuous and hybrid systems.

Fuel Ratio Trajectory: Figure 3 is shown the fuel ratio in proposed SFOFSMC and SMC in uncertain environment but without disturbance for desired.

By comparing this response, Figre 3, in SMC and SFOFSMC, conversely the SFOFSMC's overshoot is lower than SMC's, the rise time in both of methodologies have identical response. The Settling time in SFOFSMC is fairly lower than SMC.

Disturbance Rejection: Figure 4 is indicated the power disturbance removal in SMC and SFOFSMC. As mentioned by, SMC is a robust nonlinear controller which it is used as a base controller in this work. Besides a band limited white noise with predefined of 40% the power of input signal is applied to the trajectory response SMC and SFOFSMC; it found slight oscillations in classical SMC trajectory responses.

Among above graph, relating to desired trajectory following with structure and unstructured disturbance, SMC has slightly fluctuations. SFOFSMC's overshoot is lower than SMC's, SMC and SFOFSMC’s rise time are the same and finally the Settling time in SFOFSMC is quite lower than SMC.

Chattering Phenomenon: Reduce or remove the chattering in uncertain and noisy environment is plaed important role to design a good controller. Figure 5 is shown the power of boundary layer (saturation) method to reduce the chattering in SMC and SFOFSMC.

Figure 5 has indicated the power of chattering rejection in SMC and SFOFSMC, with disturbance and uncertainties. Refer to this graph, SMC has slightly fluctuations. Overall in this research in presence of uncertainty and external disturbance, SFOFSMC has the steady chattering compared to the SMC.

CONCLUSION

Refer to the research, a sliding mode fuzzy online tune fuzzy sliding mode controller is design and applied to IC engine in presence of structure and unstructured uncertainties. Regarding to the positive points in classical sliding mode controller and fuzzy sliding mode methodology and self tuning sliding mode fuzzy algorithm, the response is improved. Fuzzy logic method by adding to the sliding mode controller has covered negative points. Obviously IC engine is nonlinear and MIMO system so in proposed controller in first step design free model controller based on fuzzy sliding mode controller and after that disturbance rejection is improved by on-line sliding mode fuzzy tunable gain. Higher implementation quality of response and model free controller versus an acceptable performance in chattering, trajectory and error is reached by designing proposed 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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