

Adjust the Fuel Ratio by High Impact Chattering Free Sliding Methodology with Application to Automotive Engine

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Abstract

Fuel ratio (FR) is the mass ratio of air and fuel trapped inside a cylinder before combustion begins, and it affects engine emissions, fuel economy, and other performances. For a dual fuel engine equipped with both port-fuel-injection (PFI) and direct injection (DI) systems, the fuel ratio is the ratio of the first fuel and total fuel masses. In this research, a multi-input-multi-output baseline chattering free sliding mode methodology scheme is developed with guaranteed stability to simultaneously control fuel ratios to desired levels under various air flow disturbances by regulating the mass flow rates of engine PFI and DI injection systems. A baseline estimator with varying parameter gain is designed with guaranteed stability to allow implementation of the proposed state feedback sliding mode methodology into a MATLAB simulation environment, where the sliding mode strategy is implemented into a model engine control module (“software”). The baseline sliding methodology performance was compared with a well-tuned baseline multi-loop PID controller through MATLAB simulations and showed improvements, where MATLAB simulations were conducted to validate the feasibility of utilizing the developed controller and state estimator for automotive engines.

A baseline sliding mode tracking methodology is developed to regulate the transient and steady state FR based upon a control oriented model of the engine PFI wall wetting dynamics. The proposed tracking method is designed to optimally track the desired FR by minimizing the error between the trapped in-cylinder mass and the product of the desired FR and fuel mass over a given time interval. The performance of the optimal proposed tracking methodology was compared with the conventional fueling control based on the inverse fueling dynamics through simulations and showed improvement over the baseline conventional inverse fueling dynamics methodology.

Keywords: *nonlinear methodology to control, chattering free baseline sliding mode methodology, uncertainties, chattering phenomenon, internal combustion engine, sliding mode methodology, baseline methodology*

1. Introduction

Internal combustion engine: Modeling of an entire internal combustion (IC) engine is a very important and complicated process because internal combustion engines are nonlinear, multi inputs-multi outputs (MIMO) and time variant. There have been several engine controller designs over the previous years in which the main goal is to improve the efficiency and exhaust emissions of the automotive engine [1-4]. Specific applications of air to fuel (A/F)

ratio control based on observer measurements in the intake manifold were 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 manifold. Current production A/F ratio controllers use closed loop feedback and feed forward control to achieve the desired stoichiometric 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 [8-9].

Nonlinear Controller Methodology to FR Adjust: A nonlinear robust controller design is a major subject in this work. Controller is a device which can sense information from linear or nonlinear system to improve the systems performance [10-13]. The main targets in designing control systems are stability, good disturbance rejection, and small tracking error [14-20]. Several IC engines are controlled by linear methodologies (e.g., Proportional-Derivative (PD) controller, Proportional-Integral (PI) controller or Proportional-Integral-Derivative (PID) controller), but in uncertain dynamic models this technique has limitations [21-45].

Sliding Mode Methodology: Sliding mode methodology (SMM) is a significant nonlinear optimal control fuel ratio methodology under condition of partly uncertain dynamic parameters of system. This controller is used to control of highly nonlinear systems, because this type of optimal method is a robust and stable [11-30]. Conversely, pure sliding mode controller is used in many applications; it has two important drawbacks namely; chattering phenomenon, and nonlinear equivalent dynamic formulation in uncertain dynamic parameter [31-50]. It is possible to solve this problem by combining sliding mode controller and baseline law which this method can help improve the system's tracking performance by adjusting controller's coefficient [51-55].

Objectives: based on previous research IC engine is MIMO, nonlinear and time variant system. Sliding mode methodology is one of the robust and stable methods to tune the fuel ratio in IC engine. This method is tuned based on sliding surface slope, to adjust this parameter; based-line methodology is applied to sliding mode method. Proposed method is caused to reduce or eliminate the chattering as well as trajectory tracking fuel ratio in switching sliding mode highly stable method.

2. Theorem

Dynamic of IC 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 [6-9]. When the air-fuel mixture is compressed it causes the pressure and temperature to increase inside the cylinder. In abnormal 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. 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.

The dynamic equations of IC engine can be written as:

$$\begin{bmatrix} PFI \\ DI \end{bmatrix} = \begin{bmatrix} \dot{M}_{air11} & \dot{M}_{air12} \\ \dot{M}_{air21} & \dot{M}_{air22} \end{bmatrix} \begin{bmatrix} FR \\ \dot{\alpha}_I \end{bmatrix} + \begin{bmatrix} P_{motor1} \\ P_{motor2} \end{bmatrix} \begin{bmatrix} FR & \dot{\alpha}_I \end{bmatrix} + \begin{bmatrix} N_{11} & N_{12} \\ N_{21} & N_{22} \end{bmatrix} \times \begin{bmatrix} FR \\ \dot{\alpha}_I \end{bmatrix} + \begin{bmatrix} M_{a1} \\ M_{a2} \end{bmatrix} \quad (1)$$

There for to calculate the fuel ratio and equivalence ratio we can write:

$$\begin{bmatrix} FR_a \\ \dot{\alpha}_{I_a} \end{bmatrix} = \begin{bmatrix} \dot{M}_{air11} & \dot{M}_{air12} \\ \dot{M}_{air21} & \dot{M}_{air22} \end{bmatrix}^{-1} \left\{ \begin{bmatrix} PFI \\ DI \end{bmatrix} - \left(\begin{bmatrix} P_{motor1} \\ P_{motor2} \end{bmatrix} \begin{bmatrix} FR & \dot{\alpha}_{I_a} \end{bmatrix} + \begin{bmatrix} N_{11} & N_{12} \\ N_{21} & N_{22} \end{bmatrix} \times \begin{bmatrix} FR_a \\ \dot{\alpha}_{I_a} \end{bmatrix} + \begin{bmatrix} M_{a1} \\ M_{a2} \end{bmatrix} \right) \right\} \quad (2)$$

To solve \dot{M}_{air} , we can write;

$$\dot{M}_{air} = \begin{bmatrix} \dot{M}_{air11} & \dot{M}_{air12} \\ \dot{M}_{air21} & \dot{M}_{air22} \end{bmatrix} \quad \text{Where } \dot{M}_{air12} = \dot{M}_{air21} \quad (3)$$

Where \dot{M}_{air} is the ratio of the mass of air.

Matrix P_{motor} is a 1×2 matrix:

$$P_{motor} = \begin{bmatrix} P_1 \\ P_2 \end{bmatrix} \quad (4)$$

Matrix engine angular speed matrix(N) is a 2×2 matrix

$$N = \begin{bmatrix} N_{11} & N_{12} \\ N_{21} & N_{22} \end{bmatrix} \quad (5)$$

Where,

Matrix mass of air in cylinder for combustion matrix (M_a) is a 1×2 matrix.

$$M_a = \begin{bmatrix} M_{a1} \\ M_{a2} \end{bmatrix} \quad (6)$$

The above target equivalence ratio calculation will be combined with fuel ratio calculation that will be used for controller design purpose.

Sliding Mode methodology: Consider a nonlinear single input dynamic system is defined by [10-17]:

$$\dot{x}^{(n)} = f(\vec{x}) + b(\vec{x})u \quad (7)$$

Where u is the vector of control input, $x^{(n)}$ is the n^{th} derivation of x , $x = [x, \dot{x}, \ddot{x}, \dots, x^{(n-1)}]^T$ is the state vector, $f(x)$ is unknown or uncertainty, and $b(x)$ is of known *sign* function. The main goal to design this controller is train to the desired state; $x_d = [x_d, \dot{x}_d, \ddot{x}_d, \dots, x_d^{(n-1)}]^T$, and tracking error vector is defined by [18-30]:

$$\tilde{x} = x - x_d = [\tilde{x}, \dots, \tilde{x}^{(n-1)}]^T \quad (8)$$

A time-varying sliding surface $s(x, t)$ in the state space R^n is given by [31-45]:

$$s(x, t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} \tilde{x} = 0 \quad (9)$$

where λ is the positive constant. To further penalize tracking error, integral part can be used in sliding surface part as follows [10]:

$$s(x, t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} \left(\int_0^t \tilde{x} dt\right) = 0 \quad (10)$$

The main target in this methodology is kept the sliding surface slope $s(x, t)$ near to the zero. Therefore, one of the common strategies is to find input U outside of $s(x, t)$ [10].

$$\frac{1}{2} \frac{d}{dt} s^2(x, t) \leq -\zeta |s(x, t)| \quad (11)$$

where ζ is positive constant.

$$\text{If } S(0) > 0 \rightarrow \frac{d}{dt} S(t) \leq -\zeta \quad (12)$$

To eliminate the derivative term, it is used an integral term from $t=0$ to $t=t_{reach}$

$$\int_{t=0}^{t=t_{reach}} \frac{d}{dt} S(t) \leq -\int_{t=0}^{t=t_{reach}} \eta \rightarrow S(t_{reach}) - S(0) \leq -\zeta(t_{reach} - 0) \quad (13)$$

Where t_{reach} is the time that trajectories reach to the sliding surface so, suppose $S(t_{reach} = 0)$ defined as

$$0 - S(0) \leq -\eta(t_{reach}) \rightarrow t_{reach} \leq \frac{S(0)}{\zeta} \quad (14)$$

And

$$\text{if } S(0) < 0 \rightarrow 0 - S(0) \leq -\eta(t_{reach}) \rightarrow S(0) \leq -\zeta(t_{reach}) \rightarrow t_{reach} \leq \frac{|S(0)|}{\eta} \quad (15)$$

Equation (15) guarantees time to reach the sliding surface is smaller than $\frac{|S(0)|}{\zeta}$ since the trajectories are outside of $S(t)$.

$$\text{if } S_{t_{reach}} = S(0) \rightarrow \text{error}(x - x_d) = 0 \quad (16)$$

suppose S is defined as

$$s(x, t) = \left(\frac{d}{dt} + \lambda\right) \tilde{x} = (\dot{x} - \dot{x}_d) + \lambda(x - x_d) \quad (17)$$

The derivation of S , namely, \dot{S} can be calculated as the following;

$$\dot{S} = (\ddot{x} - \ddot{x}_d) + \lambda(\dot{x} - \dot{x}_d) \quad (18)$$

suppose the second order system is defined as;

$$\ddot{x} = f + u \rightarrow \dot{S} = f + U - \ddot{x}_d + \lambda(\dot{x} - \dot{x}_d) \quad (19)$$

Where f is the dynamic uncertain, and also since $S = 0$ and $\dot{S} = 0$, to have the best approximation, \hat{U} is defined as

$$\hat{U} = -\hat{f} + \ddot{x}_d - \lambda(\dot{x} - \dot{x}_d) \quad (20)$$

A simple solution to get the sliding condition when the dynamic parameters have uncertainty is the switching control law:

$$U_{dis} = \hat{U} - K(\vec{x}, t) \cdot \text{sgn}(s) \quad (21)$$

where the switching function $\text{sgn}(S)$ is defined as [11,16]

$$\text{sgn}(s) = \begin{cases} 1 & s > 0 \\ -1 & s < 0 \\ 0 & s = 0 \end{cases} \quad (22)$$

and the $K(\vec{x}, t)$ is the positive constant. Suppose by (11) the following equation can be written as,

$$\frac{1}{2} \frac{d}{dt} s^2(x, t) = \dot{S} \cdot S = [f - \hat{f} - K \text{sgn}(s)] \cdot S = (f - \hat{f}) \cdot S - K|S| \quad (23)$$

and if the equation (15) instead of (14) the sliding surface can be calculated as

$$s(x, t) = \left(\frac{d}{dt} + \lambda\right)^2 \left(\int_0^t \tilde{x} dt\right) = (\dot{x} - \dot{x}_d) + 2\lambda(\dot{x} - \dot{x}_d) - \lambda^2(x - x_d) \quad (24)$$

in this method the approximation of U is computed as [26]

$$\hat{U} = -\hat{f} + \ddot{x}_d - 2\lambda(\dot{x} - \dot{x}_d) + \lambda^2(x - x_d) \quad (22)$$

Baseline methodology: The design of a baseline controller to control the fuel ratio was very straight forward. Since there was an output from the fuel ratio model, this means that there would be two inputs into the baseline controller. Similarly, the output of the controller result from the two control inputs of the port fuel injector signal and direct injector signal. In a typical PID controller, the controller corrects the error between the desired output value and the measured value. Since the equivalence ratio and fuel ratio are the two measured signals, two controllers were cascaded together to control the PFI and DI inputs. The first was a PID controller that corrected the error between the desired equivalence ratio and the measured equivalence ratio; while the second was only a proportional integral (PI) controller that corrected the fuel ratio error.

$$e_1(t) = \alpha_{target}(t) - \alpha_d(t) \quad (23)$$

$$e_2(t) = Fuel\ ratio_a(t) - Fuel\ Ratio_d(t) \quad (24)$$

$$PFI_\alpha = K_{p_a} e_1 + K_{V_a} \dot{e}_1 + K_{I_a} \int e_1 \quad (25)$$

$$DI_\alpha = K_{p_b} e_1 + K_{V_b} \dot{e}_1 + K_{I_b} \int e_1 \quad (26)$$

$$PFI_F = (K_{p_c} e_2 + K_{I_c} \int e_2) \times PFI_\alpha \quad (27)$$

$$DI_F = DI_\alpha \quad (28)$$

3. Methodology

Baseline Sliding Mode Controller Methodology: The design of a baseline controller to control the sliding surface slope was very straight forward. Since there was an output from the sliding surface slope model, this means that there would be two inputs into the baseline controller. Similarly, the output of the controller result from the control input of the sliding surface slope. In a typical PID controller, the controller corrects the error between the desired output value and the measured value. Since the sliding surface slope is the measured signal, two controllers were cascaded together to control the sliding surface slope. The first was a PID method that corrected the error between the desired FR and the measured FR; while the second was only a proportional integral (PI) method that corrected the sliding surface, error and integral of error.

$$e(t) = FR_{desired}(t) - FR_{actual}(t) \quad (29)$$

$$S_\alpha = \lambda_\alpha e + \dot{e} + \left(\frac{\lambda_\alpha}{2}\right)^2 \int e \quad (30)$$

$$S_T = (\lambda_\alpha e + \left(\frac{\lambda_\alpha}{2}\right)^2 \int e) \times S_\alpha \quad (31)$$

$$S_T = (\lambda_\alpha e + \left(\frac{\lambda_\alpha}{2}\right)^2 \int e) \times (\lambda_\alpha e + \dot{e} + \left(\frac{\lambda_\alpha}{2}\right)^2 \int e) \quad (32)$$

Proof the stability: the lyapunov formulation can be written as follows,

$$V = \frac{1}{2} S_T^T \cdot \dot{M}_{air} \cdot S_T \quad (33)$$

the derivation of V can be determined as,

$$\dot{V} = \frac{1}{2} S_T^T \cdot \ddot{M}_{air} \cdot S_T + S_T^T \cdot \dot{M}_{air} \cdot \dot{S}_T \quad (34)$$

The dynamic equation of IC engine can be written based on the sliding surface as

$$\dot{M}_{air} \cdot \dot{S}_T = -VS + \dot{M}_{air} \cdot \dot{S}_T + P_{motor} + N + M_\alpha \quad (35)$$

It is assumed that

$$S_T^T(\dot{M}_{air} - 2P_{motor} + N + M_a)S_T = 0 \quad (36)$$

By substituting (35) in (24)

$$\begin{aligned} \dot{V} &= \frac{1}{2}S_T^T \dot{M}S - S_T^T P_{motor} + NS_T + S_T^T(M\dot{S} + P_{motor} + NS_T + M_a) \\ &= S_T^T(M\dot{S} + P_{motor} + NS_T + M_a) \end{aligned} \quad (37)$$

Suppose the control input is written as follows

$$\hat{U} = \left[\widehat{M}_{air}^{-1}(P_{motor} + N + M_a) + \dot{S}_T \right] \widehat{M}_{air} + K \cdot \text{sgn}(S_T) + P_{motor} + NS_T + M_a \quad (38)$$

$$\dot{V} \leq - \sum_{i=1}^n \eta_i |S_{T_i}| \quad (39)$$

Consequently the equation (39) guaranties the stability of the Lyapunov equation.

4. Results and Discussions

This section is focused on compare between baseline methodology to FR optimization (BLO) and baseline Sliding Mode methodology (BSMM). These controllers were tested by MATLAB/SIMULINK environment.

FR tracking: Based on equations in sliding mode methodology; this method performance is depended on the gain updating factor (K) and sliding surface slope coefficient (λ). These two coefficients are computed by gradient descent optimization in pure SMM. After this process the main important challenge is, optimizer is depending on sliding surface slope coefficients so baseline method is apply. Figure 1 shows FR tracking performance in BLO and BSMM without torque load disturbance.

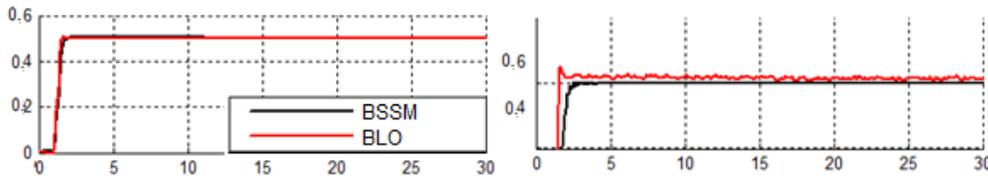


Figure 1. BSMM and BLO for Adjust FR without Torque Load Disturbance

Based on Figure 1 it is observed that, BLO has oscillation in this nonlinear system, caused to instability in tuning the FR but BSMM has steady in response. BLO's overshoot is 1.3% but BSMM's overshoot is 0%.

Disturbance rejection: Figures 2 and 3 show the power disturbance elimination in BLO and BSMM with torque load disturbance. The disturbance rejection is used to test the robustness comparisons of these two methodologies. A band limited white noise with predefined of 10% and 20% the power of input signal value is applied to this system.

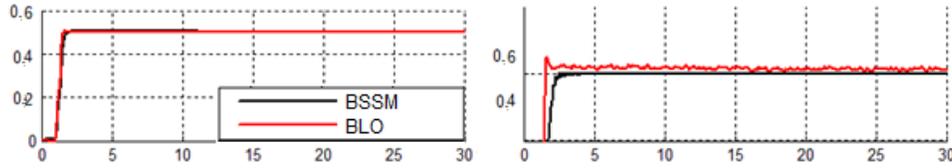


Figure 2. BSMM and BLO for Adjust FR with 10% Torque Load External Disturbance

Based on Figure 2; by comparing FR trajectory with 10% torque load disturbance of relative to the input signal amplitude in BSMM and BLO, BSMM's overshoot about (0%) is lower than BLO's (2.3%). Based on Figure 2, it is observed that BSMM's performance is better than BLO and it also can eliminate the chattering in presence of 10% disturbance.

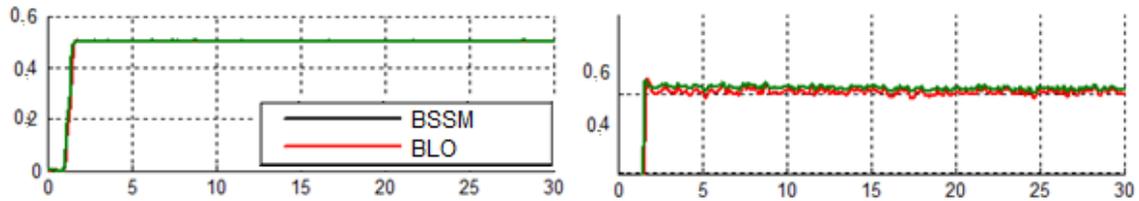


Figure 3. BSMM and BLO for Adjust FR with 20% Torque Load External Disturbance

Based on Figure 3; by comparing FR trajectory with 20% disturbance of relative to the input signal amplitude in BSMM and BLO, BSMM's overshoot about (0.32%) is lower than BLO's (3.11%). Based on Figure 3 it is observed that, these two methodologies have oscillation in presence of 20% torque load uncertainty but BSMM is more stable and more robust than BLO.

5. Conclusions

Refer to this research, a baseline sliding mode methodology is proposed for tuning the FR in internal combustion engine based on nonlinear methodology. The stability and convergence of the baseline sliding mode controller based on switching function is guarantee and proved by the LYAPUNOV method. The simulation results exhibit that the baseline sliding mode methodology tuning the FR very well in various situations. The BSMM gives significant steady state error performance when compared to BLO. The main goal in this research was reduce or eliminate the chattering that proposed methodology reach to this objective by adding baseline method to high impact robust and stable nonlinear based methodology. The second main goal in this research was reduce dependence on sliding surface slope which baseline methodology do this objective in this research. When applied 20% torque load disturbances in BSMM the RMS error increased approximately 0.1% (percent of increase the BSMM RMS error = $\frac{(20\% \text{ disturbance RMS error})}{\text{no disturbance RMS error}} = \frac{1e-5}{1e-6} = 0.1\%$) that in BLO the RMS error increased approximately 8% (percent of increase the BLO RMS error = $\frac{(20\% \text{ disturbance RMS error})}{\text{no disturbance RMS error}} = 8\%$).

Acknowledgements

The authors would like to thank the anonymous reviewers for their careful reading of this paper and for their helpful comments. This work was supported by the SSP Research and Development Corporation Program of Iran under grant no. 2012-Persian Gulf-2B.

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