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Design Model Free Switching Gain Scheduling Baseline Controller with Application to Automotive Engine

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***Abstract*—** Internal combustion (IC) engines are optimized to meet exhaust emission requirements with the best fuel economy. Closed loop combustion control is a key technology that is used to optimize the engine combustion process to achieve this goal. In order to conduct research in the area of closed loop combustion control, a control oriented cycle-to-cycle engine model, containing engine combustion information for each individual engine cycle as a function of engine crank angle, is a necessity. This research aims to design a new methodology to fix the fuel ratio in internal combustion (IC) engine. Baseline method is a linear methodology which can be used for highly nonlinear system's (e.g., IC engine). To optimize this method, new linear part sliding mode method (NLPSM) is used. This online optimizer can adjust the optimal coefficient to have the best performance.

***Index Terms*—** IC Engine, Fuel Ratio, Port Fuel Injection, Direct Injection, Baseline Method, Linear Part Sliding Mode Method

I. 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 [1-3]. 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 fuel ratio can be used to determine which fuel system should have a larger impact on how much fuel is injected into the cylinder [4-9]. Since a direct fuel injector (DI) 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. Although a port fuel injector (PFI) may have a slower response due to its wall-wetting dynamics, the fuel ratio will impact the combustion characteristics of an engine. Fuel ratio also can be used to regulate or control two fuel types. For example, an engine may have the ability to run on gasoline and ethanol. The gasoline could be injected by a PFI, while the ethanol could be injected by a DI [1-9].

Controller is a device which can sense information from linear or nonlinear system to improve the systems performance [10-20]. The main targets to design control systems (e.g., IC engines) are FR stability, good alternative torque load rejection, and small FR error[5].

Several automotive engines are controlled by linear methodologies (e.g., Proportional-Derivative (PD) controller, Proportional- Integral (PI) controller or Proportional- Integral-Derivative (PID) controller), but when this systems works with various torque loads and have uncertainty in dynamic models this technique has limitations. In some applications automotive engines are used in unknown and unstructured environment, therefore strong mathematical tools used in new control methodologies to design high performance controller with acceptable performance. Baseline controller is an influential linear cascade controller to certain and partly uncertain systems which it is free of system's dynamic model [21-40]. To control of this system linear baseline methodology is introduced. Baseline methodology (BM) is an influential linear controller to certain and partly uncertain system dynamic. This methodology is work based on system's performance. When all dynamic and physical parameters are known baseline methodology works superbly; practically a large amount of systems have external disturbance and gain scheduling methodology reduce this kind of limitation. In various dynamic parameters systems that need to be training on-line adaptive control methodology is used. Adaptive control methodology can be classified into two main groups, namely, gain scheduling method and fuzzy adaptive method [41-55]. Gain scheduling method is used in systems which main controller is work based on conventional methodology. In this research in order to solve disturbance rejection and uncertainty dynamic parameter, switching gain scheduling adaptive method is applied to baseline methodology. Sliding fuel methodology (SFM) is a powerful nonlinear robust controller under condition of partly uncertain dynamic parameters of IC engine [10-30]. Chattering phenomenon and nonlinear equivalent dynamic formulation in uncertain dynamic parameter are two main drawbacks in SFM [33-39]. The chattering phenomenon problem in SFM is reduced by using linear saturation boundary layer function but proves the stability is very difficult and increases the error. Baseline partly sliding fuel method (BPSFM) is an influential nonlinear method optimizer to certain and partly uncertain systems which it is based on combine baseline and partly sliding mode method.

II. Theory

2.1 Dynamic Formulation of IC Engine

Dynamic modeling of IC engine is used to describe the nonlinear behavior of IC engine, design of model based controller such as pure variable structure controller based on nonlinear dynamic equations, and for simulation. The dynamic modeling describes the relationship between fuel to air ratio to PFI and DI and also it can be used to describe the particular dynamic effects (e.g., motor pressure, angular speed, mass of air in cylinder, and the other parameters) to behavior of system[1].

The equation of an IC engine governed by the following equation [1, 4, 25, 29, 43-44]:

$$\begin{aligned}\begin{bmatrix}\mathbf{PFI}\\ \mathbf{DI}\end{bmatrix} = \begin{bmatrix}\dot{\mathbf{M}}_{\mathbf{air}\,\mathbf{11}} & \dot{\mathbf{M}}_{\mathbf{air}\,\mathbf{12}}\\ \dot{\mathbf{M}}_{\mathbf{air}\,\mathbf{21}} & \dot{\mathbf{M}}_{\mathbf{air}\,\mathbf{22}}\end{bmatrix}\begin{bmatrix}\dot{\mathbf{FR}}\\ \ddot{\alpha}_{\mathbf{I}}\end{bmatrix} &+ \begin{bmatrix}\mathbf{P}_{\mathbf{motor}\,\mathbf{1}}\\ \mathbf{P}_{\mathbf{motor}\,\mathbf{2}}\end{bmatrix}\begin{bmatrix}\dot{\mathbf{FR}} & \dot{\alpha}_{\mathbf{I}}\end{bmatrix}\\ &+ \begin{bmatrix}\mathbf{N}_{\mathbf{11}} & \mathbf{N}_{\mathbf{12}}\\ \mathbf{N}_{\mathbf{21}} & \mathbf{N}_{\mathbf{22}}\end{bmatrix} \times \begin{bmatrix}\dot{\mathbf{FR}}\\ \dot{\alpha}_{\mathbf{I}}\end{bmatrix}^2\\ &+ \begin{bmatrix}\mathbf{M}_{\mathbf{a}\,\mathbf{1}}\\ \mathbf{M}_{\mathbf{a}\,\mathbf{2}}\end{bmatrix}\end{aligned} \qquad (1)$$

Where PFI is port fuel injector, DI is direct injector, $\dot{\mathbf{M}}_{\mathbf{air}}$ is a symmetric and positive define mass of air matrix, $\mathbf{P}_{\mathbf{motor}}$ is the pressure of motor, N is engine angular speed and $\mathbf{M}_{\mathbf{a}}$ is matrix mass of air in cylinder. Fuel ratio and exhaust angle are calculated by [25, 29, 43-44]:

$$\begin{aligned}\begin{bmatrix}\ddot{FR}_a\\ \ddot{\alpha}_{I_a}\end{bmatrix} = \begin{bmatrix}\dot{M}_{air\,11} & \dot{M}_{air\,12}\\ \dot{M}_{air\,21} & \dot{M}_{air\,22}\end{bmatrix}^{-1} &\left\{\begin{bmatrix}PFI\\ DI\end{bmatrix}\right.\\ &- \left\{\begin{bmatrix}P_{motor\,1}\\ P_{motor\,2}\end{bmatrix}\begin{bmatrix}\dot{FR} & \dot{\alpha}_{I_a}\end{bmatrix}\right.\\ &+ \begin{bmatrix}N_{11} & N_{12}\\ N_{21} & N_{22}\end{bmatrix}\\ &\left.\left.\times \begin{bmatrix}\dot{FR}_a\\ \dot{\alpha}_{I_a}\end{bmatrix}^2 + \begin{bmatrix}M_{a\,1}\\ M_{a\,2}\end{bmatrix}\right\}\right\}\end{aligned} \qquad (2)$$

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

2.2 Baseline Methodology

Design of a baseline methodology to control of 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 method, the controller corrects the error between the desired input 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. Figure 1 is shown based line methodology, applied to IC engine.

$$e_1(t) = \alpha_{target}(t) - \alpha_d(t) \tag{3}$$

$$e_2(t) = Fuel\ ratio_a(t) - Fuel\ Ratio_d(t) \tag{4}$$

$$PFI_\alpha = K_{p_a} e_1 + K_{V_a} \dot{e_1} + K_{I_a} \sum e_1 \tag{5}$$

$$DI_\alpha = K_{p_b} e_1 + K_{V_b} \dot{e_1} + K_{I_b} \sum e_1 \tag{6}$$

$$PFI_F = (K_{p_c} e_2 + K_{I_c} \sum e_2) \times PFI_\alpha \tag{7}$$

$$DI_F = DI_\alpha \tag{8}$$

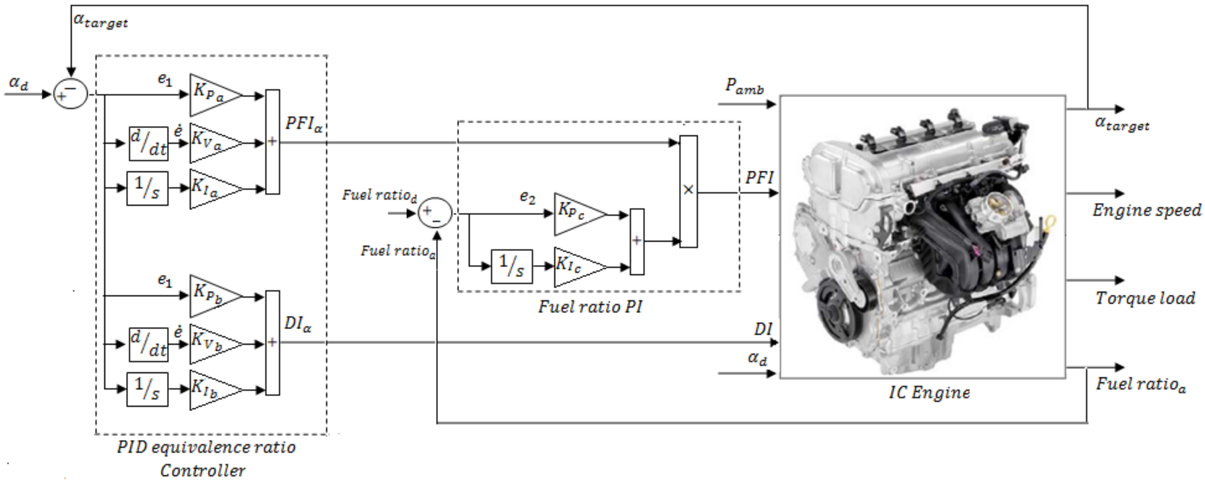

Fig. 1: Block diagram of baseline method

2.3 Sliding Fuel Methodology

Consider a nonlinear single input dynamic system is defined by [11]:

$$x^{(n)} = f(\vec{x}) + b(\vec{x})u \tag{9}$$

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 trucking error vector is defined by [16]:

$$\tilde{x} = x - x_d = [\tilde{x}, \dots, \tilde{x}^{(n-1)}]^T \tag{10}$$

A time-varying sliding surface $s(x,t)$ in the state space R^n is given by [22]:

$$s(x,t) = (\frac{d}{dt} + \lambda)^{n-1} \tilde{x} = 0 \tag{11}$$

where λ is the positive constant and calculate it is play important role to have the best performance. 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 $s(x,t)$ [28].

$$\frac{1}{2}\frac{d}{dt} s^2(x,t) \le -\zeta |s(x,t)| \tag{12}$$

where ζ is positive constant.

$$\text{If } S(0)>0 \rightarrow \frac{d}{dt} S(t) \le -\zeta \tag{13}$$

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

$$\int_{t=0}^{t=t_{reach}} \frac{d}{dt} S(t) \le -\int_{t=0}^{t=t_{reach}} \eta \rightarrow S(t_{reach}) - S(0) \le -\zeta(t_{reach} - 0) \tag{14}$$

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

$$0 - S(0) \le -\eta(t_{reach}) \rightarrow t_{reach} \le \frac{S(0)}{\zeta} \tag{15}$$

and

$$if\ S(0) < 0 \rightarrow 0 - S(0) \le -\eta(t_{reach}) \rightarrow S(0) \le -\zeta(t_{reach}) \rightarrow t_{reach} \le \frac{|S(0)|}{\eta} \tag{16}$$

Equation (11) guarantees time to reach the sliding surface is smaller than $\frac{|S(0)|}{\zeta}$ since the trajectories are outside of $S(t)$.

$$if\ S_{t_{reach}} = S(0) \rightarrow error(x - x_d) = 0 \tag{17}$$

suppose S is defined as

$$s(x,t) = (\frac{d}{dt} + \lambda)\ \ \tilde{x} = (\dot{x} - \dot{x}_d) + \lambda(x - x_d) \tag{18}$$

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

$$\dot{S} = (\ddot{x} - \ddot{x}_d) + \lambda(\dot{x} - \dot{x}_d) \tag{19}$$

A simple solution to get the sliding surface condition when the dynamic parameters have uncertainty is the switching control law [21-55]:

$$U_{dis} = \hat{U} - K(\vec{x},t) \cdot \mathrm{sgn}(s) \tag{20}$$

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

$$sgn(s) = \begin{cases} 1 & s > 0 \\ -1 & s < 0 \\ 0 & s = 0 \end{cases} \tag{21}$$

and the $K(\vec{x},t)$ is the positive constant. Suppose by (7) the following equation can be written as,

$$\frac{1}{2}\frac{d}{dt} s^2(x,t) = \dot{S} \cdot S = [f - \hat{f} - K\mathrm{sgn}(s)] \cdot S = (f - \hat{f}) \cdot S - K|S| \tag{22}$$

and if the equation (11) instead of (10) the sliding surface can be calculated as

$$s(x,t) = (\frac{d}{dt} + \lambda)^2 \left(\int_0^t \tilde{x}\, dt\right) = (\dot{x} - \dot{x}_d) + 2\lambda(\dot{x} - \dot{x}_d) - \lambda^2(x - x_d) \tag{23}$$

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

$$\hat{U} = -\hat{f} + \ddot{x}_d - 2\lambda(\dot{x} - \dot{x}_d) + \lambda^2(x - x_d) \tag{24}$$

III. Methodology

Proposed methodology is focused on applied switching method in baseline methodology to increased stability of the main controller. Switching methodology is a nonlinear robust and stable method and linear baseline method is a nonlinear controller but it has a challenge in stability and robustness especially in presence of uncertainty and disturbance. Based on (13) to improve stability switching formulation is applied to baseline methodology;

$$\tau = PFI \times sgn(\ddot{q}_d + K_v((\ddot{x} - \ddot{x}_d) + \lambda(\dot{x} - \dot{x}_d)) + K_p((\dot{x} - \dot{x}_d) + \lambda(x - x_d)\ )) \tag{25}$$

To resolve uncertain problem this research is focused on to design SISO sliding mode switching baseline methodology. According to the linear system theory, convergence of the tracking error to zero is guaranteed [6]. Supervisory gains adjusted by partly sliding mode method. The result scheme is shown in Figure 2.

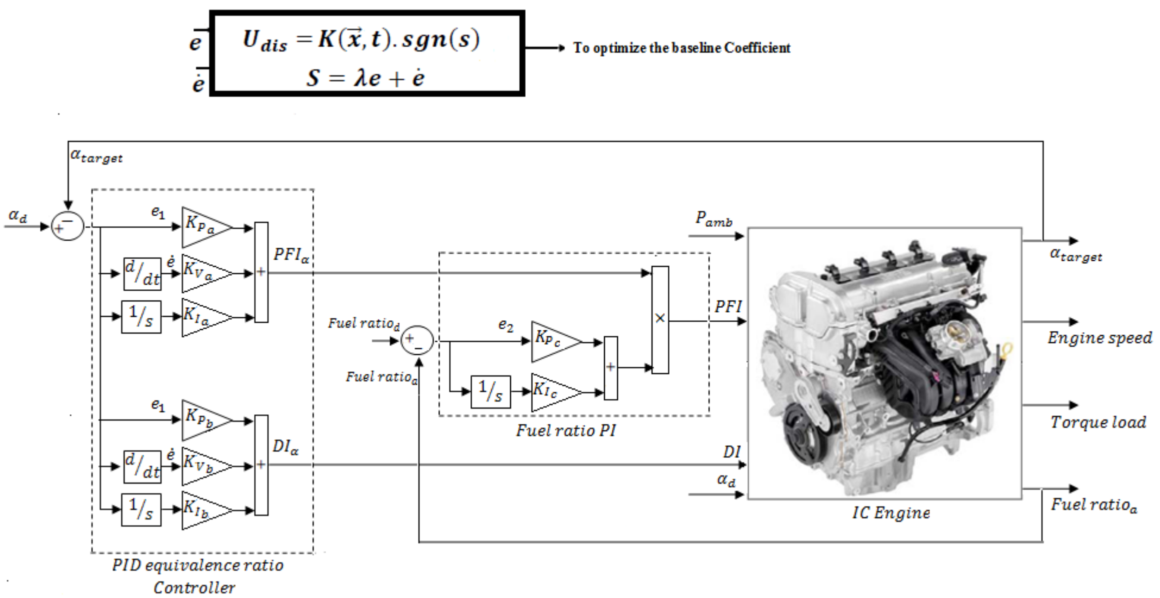

Fig. 2: Block diagram of a partly sliding mode optimizer baseline method: applied to IC engine

IV. Results and Discussion

This part is focused on compare between baseline method (BM) and baseline partly sliding mode fuel method (BPSFM). These two methods were tested by step fuel ratio and equivalence ratio. The simulation was implemented in MATLAB/SIMULINK environment.

Close loop response of fuel ratio without any disturbance: Figure 3 is shown the methodology of fuel ratio based on two methods: BPSFM and BM.

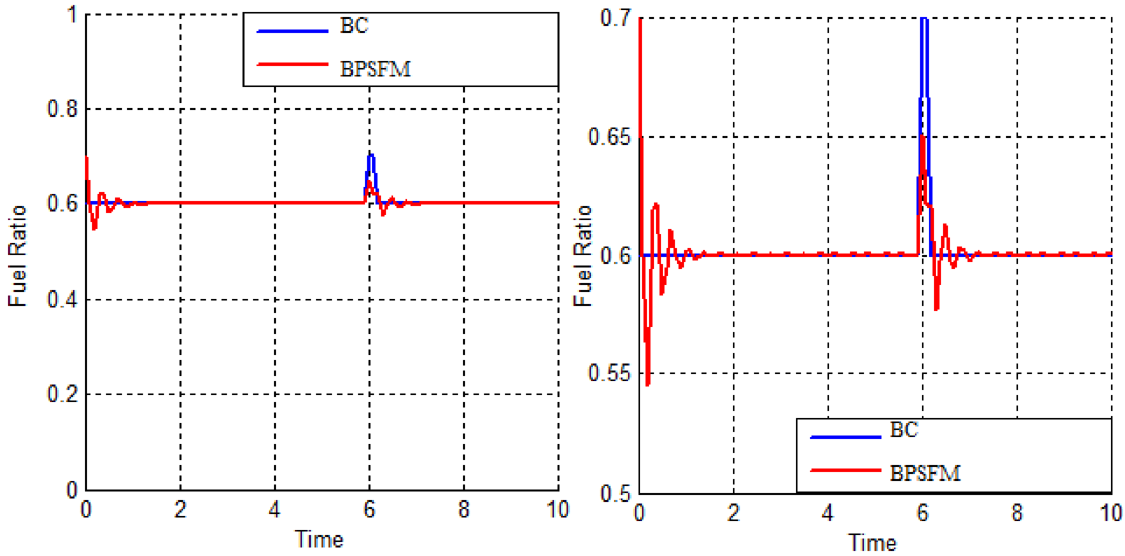

Fig. 3: BM vs. BPSFM without disturbance

Based on Figure 3; by comparing fuel ratio response without disturbance in BM and BPSFM, BPSFM's overshoot about **(0.0%)** is lower than BC's **(18%).**

Close loop response of fuel ratio in presence of torque load disturbance: Figure 4 shows the power disturbance elimination in BPSFM and BM with torque load disturbance for fuel ratio. The disturbance rejection is used to test the robustness comparisons of these two methodologies for fuel ratio. It found fairly fluctuations in BM responses.

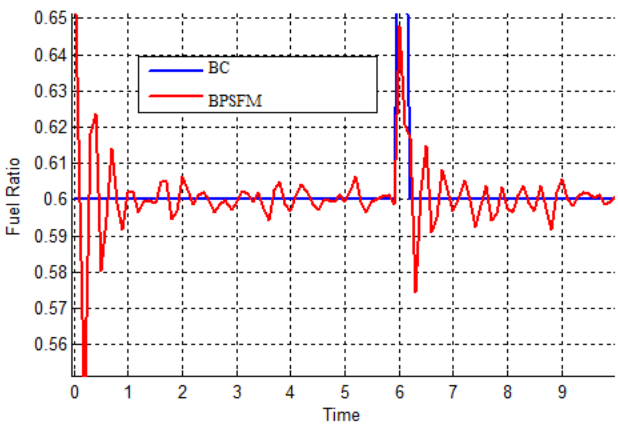

Fig. 4: BM vs. BPSFM with torque load disturbance

Based on Figure 4; by comparing fuel ratio response in presence of torque load disturbance in BM and BPSFM, BPSFM's overshoot about (0%) is lower than BM's **(23%).** Based on Figure 4, BM has moderately oscillation in fuel ratio response with regard to torque load disturbance but BPSFM has stability in trajectory responses.

V. Conclusion

This paper reveals a new method for supervisory control of IC engine to reduce the fuel and fix the fuel ratio .This method is used to simultaneously control the mass flow rate of both port fuel injection (PFI) and direct injection (DI) systems to regulate the fuel ratio of PFI to DI to desired levels. The research results explain the supervisory performance of IC engine. In this context, this research proposes a new linear baseline methodologies for IC engine to reach the following target, improvement the fuel ratio performance by online tuning the baseline optimizer, development of system's supervisory method by new linear method, develop the business by design a small and cheaper controller model.

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