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Baseline Tuning Methodology Supervisory Sliding Mode Methodology: Applied to IC 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.

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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, bio-fuels, and hydrogen. The output power produced by an IC engine results from the fuel, that it uses, and also its mechanical parts. 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 [1-8]. 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

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. Analytical dynamic nonlinear modeling of internal combustion engine is carried out using elegant Euler-Lagrange method compromising accuracy and complexity. An empirical dynamic nonlinear model of the system is then developed on the bases of neural network and/or neuro-fuzzy. The developed models are verified using several testing approaches such as overlapping, power spectral density and correlation tests [3], [4], [5], [9-16]. The sum of the fuel that is injected into the cylinder by the port fuel injector and the direct fuel injector is the total fuel, $\dot{M}_{Fuel}$. The amount of fuel injected by one injector divided by the sum of the two is the fuel ratio of PFI to DI. 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. Although a port fuel injector 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 port fuel injector, while the ethanol could be injected by a direct injector. Although, implementation of this may require to separate fuel lines and separate fuel tanks, the ratio of gasoline to ethanol, or two other types of fuels, may be of interest to future engine control designers. Controller is a device which can sense information from linear or nonlinear system (e.g., IC engine) to improve the systems performance [3]. 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.

This paper is organized as follows. In section 2, main subject of dynamic formulation of IC engine is presented. A methodology of proposed baseline partly sliding fuel methodology is presented in section 3. In section 4, the baseline method and proposed methodology are compared and discussed. In section 5, the conclusion is presented.

2. THEOREM: DYNAMIC FORMULATION OF IC ENGINE’S FUEL RATIO

The dynamic equations of IC engine can be written as:

$$\begin{bmatrix} \mathrm{PFI} \\ \mathrm{DI} \end{bmatrix} = \begin{bmatrix} \dot{\mathrm{M}}_{\mathrm{air}_{11}} & \dot{\mathrm{M}}_{\mathrm{air}_{12}} \\ \dot{\mathrm{M}}_{\mathrm{air}_{21}} & \dot{\mathrm{M}}_{\mathrm{air}_{22}} \end{bmatrix} \begin{bmatrix} \ddot{\mathrm{FR}} \\ \ddot{\alpha}_{\mathrm{I}} \end{bmatrix} + \begin{bmatrix} \mathrm{P}_{\mathrm{motor}_1} \\ \mathrm{P}_{\mathrm{motor}_2} \end{bmatrix} \begin{bmatrix} \dot{\mathrm{FR}} & \dot{\alpha}_{\mathrm{I}} \end{bmatrix} + \begin{bmatrix} \mathrm{N}_{11} & \mathrm{N}_{12} \\ \mathrm{N}_{21} & \mathrm{N}_{22} \end{bmatrix} \times \begin{bmatrix} \dot{\mathrm{FR}} \\ \dot{\alpha}_{\mathrm{I}} \end{bmatrix}^2 + \begin{bmatrix} \mathrm{M}_{\mathrm{a}_1} \\ \mathrm{M}_{\mathrm{a}_2} \end{bmatrix} \qquad (1)$$

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

$$\begin{bmatrix} \ddot{\mathrm{FR}}_{\mathrm{a}} \\ \ddot{\alpha}_{\mathrm{I}_{\mathrm{a}}} \end{bmatrix} = \begin{bmatrix} \dot{\mathrm{M}}_{\mathrm{air}_{11}} & \dot{\mathrm{M}}_{\mathrm{air}_{12}} \\ \dot{\mathrm{M}}_{\mathrm{air}_{21}} & \dot{\mathrm{M}}_{\mathrm{air}_{22}} \end{bmatrix}^{-1} \left\{ \begin{bmatrix} \mathrm{PFI} \\ \mathrm{DI} \end{bmatrix} - \left\{ \begin{bmatrix} \mathrm{P}_{\mathrm{motor}_1} \\ \mathrm{P}_{\mathrm{motor}_2} \end{bmatrix} \begin{bmatrix} \dot{\mathrm{FR}} & \dot{\alpha}_{\mathrm{I}_{\mathrm{a}}} \end{bmatrix} + \begin{bmatrix} \mathrm{N}_{11} & \mathrm{N}_{12} \\ \mathrm{N}_{21} & \mathrm{N}_{22} \end{bmatrix} \times \begin{bmatrix} \dot{\mathrm{FR}}_{\mathrm{a}} \\ \dot{\alpha}_{\mathrm{I}_{\mathrm{a}}} \end{bmatrix}^2 + \begin{bmatrix} \mathrm{M}_{\mathrm{a}_1} \\ \mathrm{M}_{\mathrm{a}_2} \end{bmatrix} \right\} \right\} \qquad (2)$$

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

$$\dot{\mathrm{M}}_{\mathrm{air}} = \begin{bmatrix} \dot{\mathrm{M}}_{\mathrm{air}_{11}} & \dot{\mathrm{M}}_{\mathrm{air}_{12}} \\ \dot{\mathrm{M}}_{\mathrm{air}_{21}} & \dot{\mathrm{M}}_{\mathrm{air}_{22}} \end{bmatrix} \qquad \text{Where } \dot{\mathrm{M}}_{\mathrm{air}_{12}} = \dot{\mathrm{M}}_{\mathrm{air}_{21}} \qquad (3)$$

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

Mair11=(Pamb)+(AtoF)+2*(IF1)*cos(FR)*cos(FR)+(IF2)*sin(FR+alfa)*sin(FR+alfa)+(IF3)*sin(FR+alfa)*cos(FR+alfa)+0.10299*sin(FR)*cos(FR);

Mair12=(Pamb)*sin(FR)+(AtoF)*cos(FR+alfa)+(IF1)*cos(FR)+(IF2)*sin(FR+alfa);

Mair21=Mair12;

Mair22=(IF1)+(IF2)+(IF3)+(2*(Pamb)*sin(alfa))+(IF4)*cos(FR);

Matrix P_{motor} is a 1×2 matrix:

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

Where,
P1=- 4*(AtoF)*sin(FR)*cos(FR)+(Pamb)*cos(FR+FR+alfa)+(IF1)*sin(FR+alfa)*cos(FR+alfa);
P2=2.821-0.05231*cos(FR+alfa)+0.10299*sin(FR)*cos(FR)-0.00063*cos(FR)*(FR);

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,
torque_engine=(IF4)*cos(FR)-(Pamb)*sin(FR+alfa)-((AtoF))*sin(FR);
N11=(IF4)*cos(FR)-(Pamb)*sin(FR+alfa)*J;
N12=2*(torque_engine/J);
N21=2*(Pamb)*cos(FR)*sin(FR);
N22=-N12+N11;

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

$$M_a = \begin{bmatrix} M_{a_1} \\ M_{a_2} \end{bmatrix} \quad (6)$$

Where,
Ma1=IF1*cos(FR)+IF2*sin(FR+alfa)+IF3*sin(FR)+IF4*cos(FR+alfa)+Pamb*sin(FR+alfa);
Ma2=Pamb*sin(FR+alfa);

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

3. METHODOLOGY: BASELINE PARTLY SLIDING MODE FUEL OPTIMIZATION FOR IC ENGINE

Baseline Controller Design: 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. Figure 1 shows the two cascaded controllers.

$$\boldsymbol{e_1(t) = \alpha_{target}(t) - \alpha_d(t)} \quad (7)$$

$$\boldsymbol{e_2(t) = Fuel\,ratio_a(t) - Fuel\,Ratio_d(t)} \quad (8)$$

$$\boldsymbol{PFI_\alpha = K_{p_a} e_1 + K_{V_a} \dot{e_1} + K_{I_a} \sum e_1} \quad (9)$$

$$\boldsymbol{DI_\alpha = K_{p_b} e_1 + K_{V_b} \dot{e_1} + K_{I_b} \sum e_1} \quad (10)$$

$$\boldsymbol{PFI_F = (K_{p_c} e_2 + K_{I_c} \sum e_2) \times PFI_\alpha} \quad (11)$$

$$\boldsymbol{DI_F = DI_\alpha} \quad (12)$$

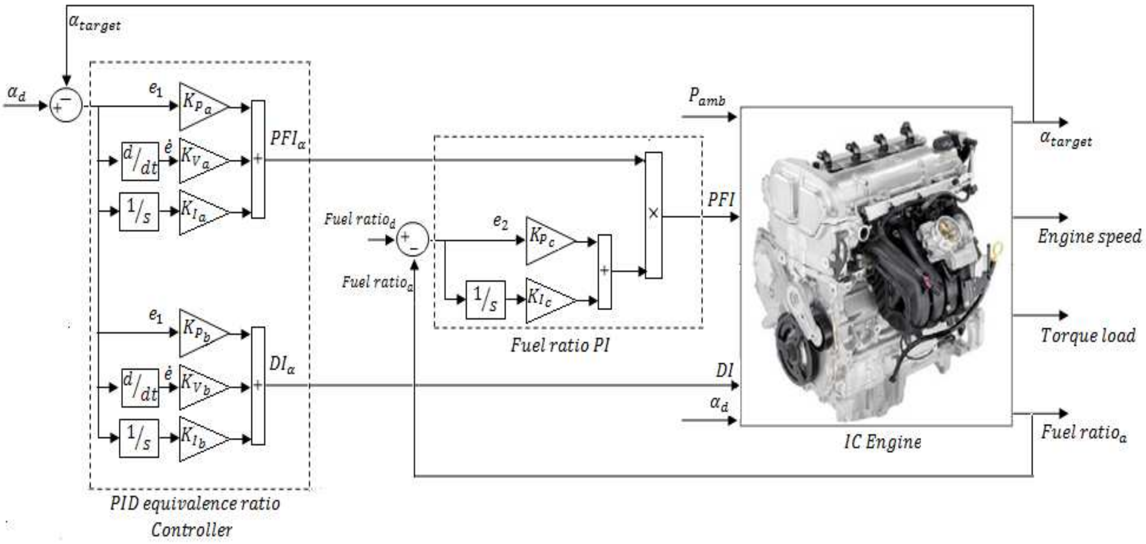

Figure 1. Block diagram of BASELINE controller

Partly Sliding Mode Fuel Methodology**:** Based on variable structure discussion, the supervisory optimizer for an IC engine is written as [18-24]:

$$\boldsymbol{U = U_{Nonlinear} + U_{linear\ based}} \tag{13}$$

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

$$\boldsymbol{U_{Nonlinear}} = \left[\boldsymbol{\dot{M}^{-1}}_{\boldsymbol{air}} \left(\begin{bmatrix} \boldsymbol{P_{motor_1}} \\ \boldsymbol{P_{motor_2}} \end{bmatrix} \begin{bmatrix} \boldsymbol{\dot{FR}} & \boldsymbol{\dot{\alpha}_I} \end{bmatrix} + \begin{bmatrix} \boldsymbol{N_{11}} & \boldsymbol{N_{12}} \\ \boldsymbol{N_{21}} & \boldsymbol{N_{22}} \end{bmatrix} \times \begin{bmatrix} \boldsymbol{\dot{FR}} \\ \boldsymbol{\dot{\alpha}_I} \end{bmatrix}^2 + \begin{bmatrix} \boldsymbol{M_{a_1}} \\ \boldsymbol{M_{a_2}} \end{bmatrix} \right) + \boldsymbol{\dot{S}} \right] \boldsymbol{\dot{M}_{air}} \tag{14}$$

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

$$\boldsymbol{U_{dis} = K(\vec{x}, t) \cdot \mathbf{sgn}(s)} \tag{15}$$

where the switching function $\mathbf{sgn}(\boldsymbol{S})$ is defined as

$$\boldsymbol{sgn(s)} = \begin{cases} \mathbf{1} & \boldsymbol{s} > 0 \\ \mathbf{-1} & \boldsymbol{s} < 0 \\ \mathbf{0} & \boldsymbol{s = 0} \end{cases} \tag{16}$$

and the $\boldsymbol{K(\vec{x}, t)}$ is the positive constant.

the lyapunov formulation can be written as follows,

$$\boldsymbol{V = \frac{1}{2} S^T . \dot{M}_{air} . S} \tag{17}$$

the derivation of V can be determined as,

$$\boldsymbol{\dot{V} = \frac{1}{2} S^T . \dot{\dot{M}}_{air} . S + S^T\ \dot{M}_{air} \dot{S}} \tag{18}$$

Figure 2 is shown pure variable structure controller, applied to IC engine.

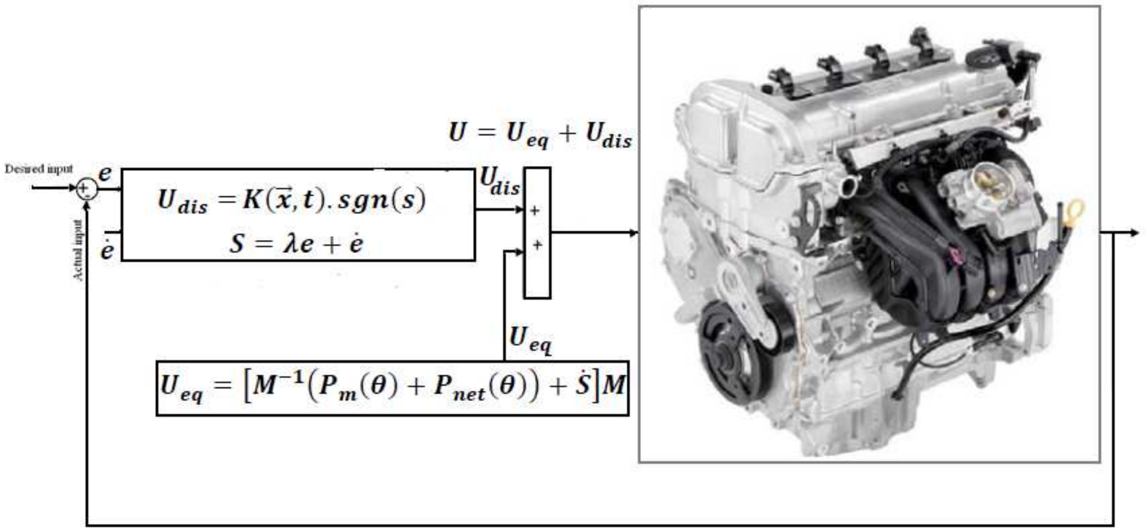

Figure 2. Block diagram of a sliding mode method: applied to IC engine

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 3.

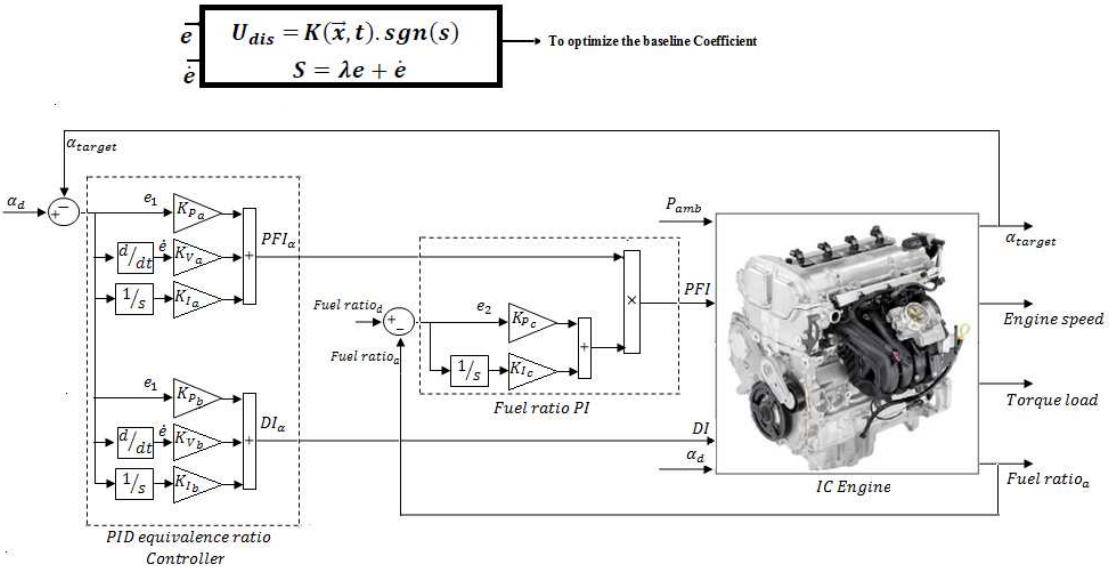

Figure 3. Block diagram of a partly sliding mode optimizer baseline method: applied to IC engine

4. RESULTS

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.

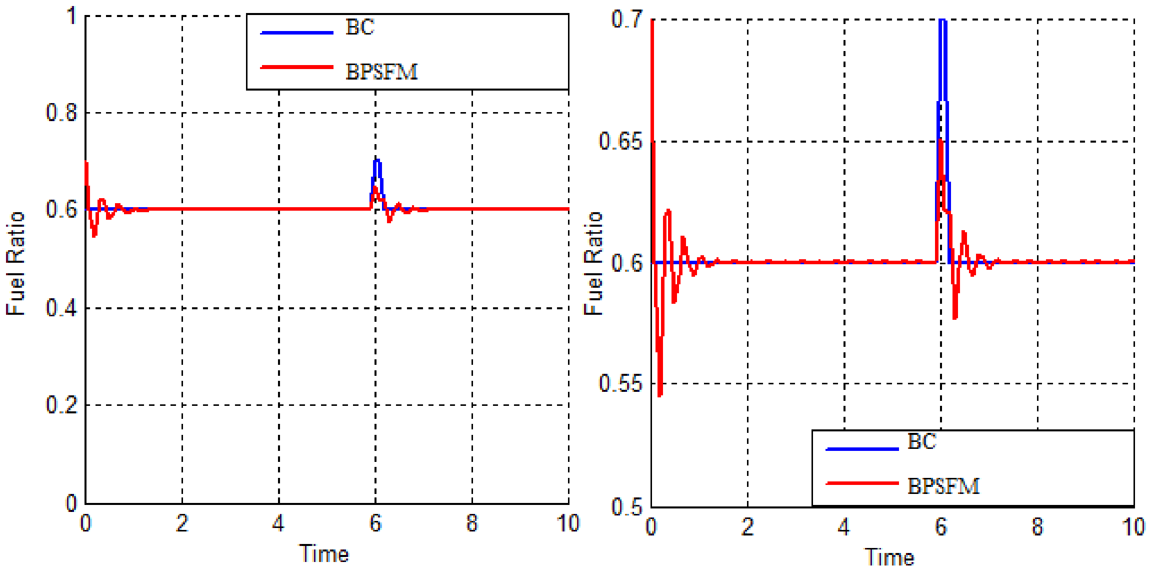

Figure 4 BM Vs. BPSFM without disturbance

Based on Figure 4; 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 5 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.

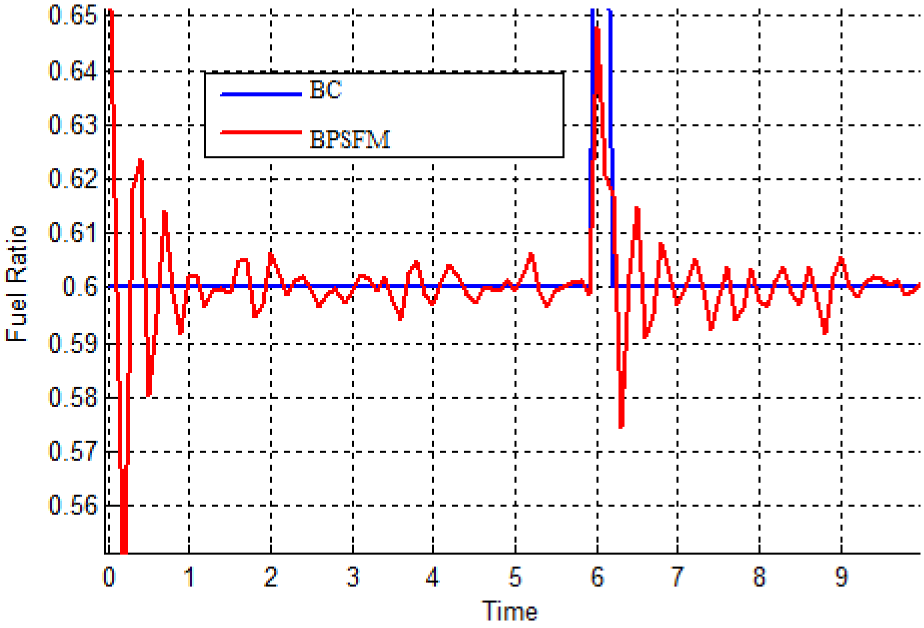

Figure 5 BM Vs. BPSFM with torque load disturbance

Based on Figure 5; 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 5, BM has moderately oscillation in fuel ratio response with regard to torque load disturbance but BPSFM has stability in trajectory responses.

5. 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, such as:1) improvement the fuel ratio performance, by online tuning the baseline optimizer 2) development of system’s supervisory method by new linear method 3) develop the business by design a small and cheaper controller.

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