Individual Air-Fuel Ratio Balancing Control for Multi-Cylinder SI Engines: Modeling and Validation

Po Li* Tielong Shen**

* Department of Mechanical and Electrical Engineering, Xiamen University, Xiamen, China, (e-mail: lipo@xmu.edu.cn).
** Department of Engineering and Applied Science, Sophia University, Tokyo, Japan, (e-mail: tetu-sin@sophia.ac.jp)

Abstract: The three phase catalyst is popularly employed in modern engines for exhaust control and its catalytic efficiency is determined by the Air-Fuel ratio (A/F). In this paper, individual A/F control problem is addressed for a multi-cylinder SI engine, of which one exhaust pipe is shared by many cylinders. Firstly, an overlap model to describe the dynamics from individual fuel injection to A/F value of mixing point at the exhaust pipe is introduced. In this model, the imbalance between cylinders in A/F is presented by unknown offsets in individual fuel injection. Then the unknown offset free Model Predictive Control (MPC) scheme is designed based on this model. Finally, both the model and the controller are validated by a car-used six-cylinder SI engine.

1. INTRODUCTION

Environmental conservation leads to increasing strict emission regulation for modern auto industry. For example, the threshold in exhausting profile is set as the market access condition for new vehicles. From last 80s, the three phase catalytic converter was equipped in SI engines as an available way to reduce the toxicity of emission. However, the A/F leaves a profound influence on the catalytic efficiency. For gasoline engines, the highest catalytic efficiency is reached when A/F is 14.7. Hence A/F control is one of the important topics in advanced engine control. For multi-cylinder engines, the exhaust pipes are shared by many cylinders. Intuitively, to keep the A/F profile at 14.7 for each cylinder is not only to obtain better catalytic efficiency, but also to improve fuel efficiency. Then individual A/F control from the measurement of fluctuation in A/F profile at mixing point in exhaust pipe has drawn lots of attentions in the last decade. For instance, [1], [2] and [3] illustrated some observer techniques for estimation of individual A/F profiles, based on which, individual control law can be found in [4]. The individual A/F ratio balancing problem is also studied in this paper and the main contributions include:

(1) Based on the proposed models ([3] [4]), an overlap model for the dynamics from individual fuel injection to the A/F at mixing point is established. Based on this model, a condition is found. If the condition is satisfied, to keep A/F at mixing point to the expected value can lead to individual A/F balancing control.

(2) Based on the overlap model, the unknown offset free MPC controller is designed, which is finally validated by experiments to keep individual A/F at 14.7 by only using the A/F at mixing point as the feedback signal.

The exhaust system for multi-cylinder SI engines is simply shown in Fig.1. A lambda sensor (for A/F detection) is located at the mixing point in the exhaust pipe before the three phase catalyst. The exhaust gas from individual runner enters the exhaust pipe one by one and then mixes for emission. Our concern is the A/F loop, where the control input is individual fuel injection and the feedback signal is the A/F value at mixing point. For the $i$-th cylinder of a $n$ cylinder engine located at the $k$-th combustion cycle, let $\lambda_i(k)$ denote its A/F value, we have

$$\lambda_i(k) = \frac{m_a}{r_{fi}(k)} \quad i = 1, 2, \cdots, n \quad (1)$$

where $m_a$ is the nominal exact air mass and $r_{fi}(k)$ is the exact fuel for combustion.

Fig. 1. Exhausting process for a 6-cylinder engine (from the right view where cylinder 2, 4 and 6 share the same exhaust pipe)

However, in (1) the input variables are located as denominators. To avoid the nonlinear deduced from the definition, another index $F/G$ is introduced as (2)

$$\eta_i(k) = \frac{r_{fi}(k)}{m_a + r_{fi}(k)} = \frac{1}{1 + \lambda_i(k)} \quad i = 1, 2, \cdots, n \quad (2)$$
In this study, the balancing control is to keep F/G value of every cylinder to \( \frac{1}{14.7} \). For direct injection engines, let \( cf_i(k) \) denote the fuel injection command for the \( i \)-th cylinder and \( B_i \) be the unknown offset due to aging or manufacture tolerance. Then we have

\[
r_f(k) = cf_i(k) + B_i + d_i(k) \quad i = 1, 2, \ldots, n \tag{3}
\]

where \( d_i(k) \) denotes the noise effect. For engines work under steady operation modes, \( B_i \) can be seen as a constant or changing slowly, i.e. \( B_i(k+1) - B_i(k) = 0 \).

Before modeling, some feasible hypothesis are taken for the engine system works under a steady operation point, these assumptions can also be found in [3] and [4].

\( S1 \): The mass in combustion for each cylinder (\( m_i \)) can be taken as constant, i.e. \( m_i = m_a + r_f_i(k) \) is constant \( i = 1, 2, \ldots, n \). For an engine works under steady operation modes near stoichiometric point (\( A/F \approx 14.7 \)), the air mass in combustion is much more (more than 10 times) than that of fuel. Even the adjustment in fuel injection from the controller observably influences \( A/F \) value, the fluctuation of the combustion mass is too small to be ignored.

\( S2 \): For each cylinder, there doesn’t exist overlap effect in exhaust process between two consecutive combustion cycles.

\( S3 \): For each cylinder, the gas mixing in each runner can be neglected. Hence, when combined with \( S2 \) the F/G value in each exhaust runner is constant during one combustion cycle.

\( S4 \): For the \( i \)-th cylinder, the mass flow at the exhaust valve (\( \dot{m}_i^e(\theta) \)) is a periodic function in crank angle domain. i.e.

\[
\dot{m}_i^e(\theta + 4\pi) = \dot{m}_i^e(\theta)
\]

### 3. OVERLAP MODELING AND CONTROLLER DESIGN

#### 3.1 Modeling

The exhaust process can be divided into three parts, which are expanded process, mixing process and sensor dynamics. Models for these process are discussed one by one.

The air flow from the exhaust valve to the mixing point for each cylinder is called as the expanded process, the dynamics of which can be described by a first-order inertial model (4) \( i \)-th cylinder.

\[
g^i_T(s) = \frac{1}{1 + T_is} \tag{4}
\]

where the time constant \( T_i \) is determined by the distance of the exhaust runner and engine speed. For a multi-cylinder SI engine, if the distance from each runner to the mixing point is equal, the time constant \( T_i \) is the same. According to \( S4 \), the mass flow for each cylinder at the mixing point is periodic in crank angle domain.

For a \( n \) cylinder SI engine, one exhaust pipe is shared by \( n_c \) cylinders. To simplify the notations, we use superscript to indicate the ignition order. For example, in the test bench, cylinder 2, 4 and 6 share the right exhaust pipe, then we use the following notation to present F/G value of each cylinder

\[
\eta^{(1)}(\theta) = \eta_2(\theta), \eta^{(2)}(\theta) = \eta_4(\theta), \eta^{(3)}(\theta) = \eta_6(\theta)
\]

Denote F/G at the mixing point as \( \eta_m(\theta) \), it is easy to get

\[
\eta_m(\theta) = \sum_{i=1}^{n_c} \left( \frac{\dot{m}_i^e(\theta)\eta^{(i)}(\theta)}{\sum_{i=1}^{n_c} \dot{m}_i^e(\theta)} \right)
\]

where \( \dot{m}_i^e(\theta) \) denotes the mass flow of individual cylinder at mixing point.

By sampling at each BDC point (the span in crank angle is \( \frac{2\pi}{n_c} \)), (5) can be rewritten in discrete form as (6).

\[
\eta_m(l, S-1) = \sum_{1 \leq S \leq l} \left( \frac{\dot{m}_i^e(2\pi S + \frac{2\pi S}{n_c})\eta^{(i)}(l-2)}{\sum_{1 \leq i \leq n_c} \dot{m}_i^e(2\pi S + \frac{2\pi S}{n_c})} \right) S = 1, \ldots, n_c
\]

where \( l \) denotes the number of combustion cycles and \( S \) is the sampling number in one combustion cycle.

Let

\[
\alpha_{ij} = \frac{\dot{m}_i^e(2\pi j/n_c)}{\sum_{r=1}^{n_c} \dot{m}_r^e(2\pi j/n_c)}
\]

\[
\bar{\eta}_m(k) = [\eta_m(k, 0), \eta_m(k, 1), \ldots, \eta_m(k, n_c-1)]^T
\]

\[
\bar{\eta}(k) = [\eta^{(1)}(k), \eta^{(2)}(k), \ldots, \eta^{(n_c)}(k)]^T
\]

when combined with (5), (6) is simplified as (7).

\[
\bar{\eta}_m(k) = A_1\bar{\eta}(k-1) + A_2\bar{\eta}(k-2)
\]

where

\[
A_{1(ij)} = \begin{cases} 
\alpha_{ij} & i \geq j \\
0 & i < j 
\end{cases} \quad A_{2(ij)} = \begin{cases} 
\alpha_{ij} & i < j \\
0 & i \geq j 
\end{cases}
\]

It should be noted that the above discrete model only works for sampling at consecutive BDC points. For sampling starts at any point, similar models can be deduced. However, since the BDC point is easy for capture, the above model is employed for real application.

The dynamics of the lambda sensor can be described in discrete form[3][4] as

\[
g_s(z) = \frac{g_2z^{-m_s}}{1 - g_1z^{-1}}
\]

i.e.

\[
\eta_{ms}(k, 1) = g_1\eta_{ms}(k, 0) + g_2z^{-m_s}\eta_m(k, 0)
\]

where \( \eta_{ms} \) is the F/G value calculated from the lambda sensor, \( g_1 \) and \( g_2 \) are positive constants and satisfy \( g_1 + g_2 = 1, m_s \) is the sensor delay.
By using lifting technology [5][6][7], (8) can be rewritten as
\[
\eta_{ms}(k, n_c - 1) = y_n^0 \eta_{ms}(k - 1, n_c - 1) + \\
g_2 z^{-m_s} \left[ g_1^{n_c-1} g_1^{n_c-2} \cdots g_1^0 \eta_{ms}(k, 1) \right]_{\eta_{ms}(k, n_c - 1)}
\]

Similarly, let
\[
\tilde{\eta}_{ms}(k) = [\eta_{ms}(k, 0) \, \eta_{ms}(k, 1) \, \cdots \, \eta_{ms}(k, n_c - 1)]^T,
\]
we have (9)
\[
\tilde{\eta}_{ms}(k + 1) = G_1 \tilde{\eta}_{ms}(k) + z^{-m_s} M_1 \tilde{\eta}_{m}(k) + z^{-m_s} M_2 \tilde{\eta}_{m}(k - 1)
\]
where
\[
G_1 = g_1^{n_c} I_{n_c}
\]
\[
M_1 = g_2 \begin{bmatrix} g_1^{n_c-1} & \cdots & g_1^0 \\ \\
0 & \cdots & 0 \\ \\
0 & \cdots & 0 \\ \\
0 & \cdots & 0 \end{bmatrix}
\]
\[
M_2 = g_2 \begin{bmatrix} g_1^{n_c-1} & \cdots & g_1^0 \\ \\
0 & \cdots & 0 \\ \\
0 & \cdots & 0 \end{bmatrix}
\]

According to (7), (8) and (9), the dynamics from individual F/G to the mixing point output is
\[
\tilde{\eta}_{ms}(k + 1) = G_1 \tilde{\eta}_{ms}(k) + M_1 \tilde{\eta}_{m}(k) + M_2 \tilde{\eta}_{m}(k - 1)
\]
(10)

Remark 1: Let \( s_0 = \frac{1}{1 + m_s} \) as the target, from (8), we have
\[
\tilde{\eta}_{ms\infty} = s_0 I \Leftrightarrow \tilde{\eta}_{ms\infty} = s_0 I
\]
Similarly, if
\[
\text{rank}(M_1 + M_2(A_1 + A_2)) = n_c
\]
(11)
From (10), it is easy to get \( \tilde{\eta}_{ms\infty} = s_0 I \Rightarrow \tilde{\eta}_{\infty} = s_0 I \), i.e. if the condition (11) is satisfied, by keeping the F/G at \( s_0 \) can regulate individual A/F values directly.

For the normalization, redefine the output and input of the system as \( \tilde{Y}(k) = \eta_{ms}(k) \) and
\[
U(k) = [u^{(1)}(k) \, u^{(2)}(k) \cdots u^{(n_c)}(k)]^T,
\]
\[
u^{(i)}(k) = \frac{c f_j(k) - f_0}{m_j s_0} \quad i = 1, 2 \cdots n_c; j = 1, 2 \cdots n,
\]
where \( f_0 \) is the fuel injection command in steady operation modes. Similarly, redefine the unknown offset as
\[
B^{(i)} = B_j = \frac{b_j + f_0 - m_j s_0}{m_j s_0} \quad i = 1, 2 \cdots n_c; j = 1, 2 \cdots n
\]
\[
B = [B^{(1)} \, B^{(2)} \cdots B^{(n_c)}]^T
\]
\[
O = (M_1 + M_2) B
\]

Then the system can be rewritten in overlap model with unknown offsets (12).
\[
\begin{aligned}
x(k + 1) &= G_1 x(k) + M_1 A_1 U(k - m) + (M_1 A_2 + M_2 A_1) U(k - 1 - m) + M_2 A_2 U(k - 2 - m) + O + D_k \\
Y(k) &= x(k)
\end{aligned}
\]
(12)
where \( x \) is the states, \( O \) is unknown offsets and \( D_k \) is noise.

3.2 Unknown Offset Free MPC Controller

Based on (12), the unknown offset free MPC controller is shown in Fig. 2, which include 3 steps[8][9][10][11].

![Fig. 2. The offset free MPC scheme](image-url)

**Step 1: The Observer for the augment system**

Let
\[
\begin{aligned}
X(k) &= [x(k)]^T \\
U(k) &= M_1 A_1 U(k - m) + (M_1 A_2 + M_2 A_1) U(k - 1 - m) + M_2 A_2 U(k - 2 - m)
\end{aligned}
\]
the augmented model for (12) is (13)
\[
\begin{aligned}
X(k + 1) &= \begin{bmatrix} G_1 & I \\ 0 & I \end{bmatrix} X(k) + \begin{bmatrix} G(U(k)) \\ 0 \end{bmatrix} \\
Y(k) &= [I \, 0] X(k)
\end{aligned}
\]
(13)
Let
\[
\tilde{A} = \begin{bmatrix} G_1 & I \\ 0 & I \end{bmatrix}, \tilde{c} = \begin{bmatrix} I & 0 \end{bmatrix}
\]
Since
\[
\text{rank}(\begin{bmatrix} \tilde{c} \\ \cdots \tilde{c} \tilde{A} \end{bmatrix}) = \text{rank}(\begin{bmatrix} \tilde{c} \\ \cdots \tilde{c} \tilde{A} \end{bmatrix}) = 2n_c
\]
the augment system is observable, i.e. there exists matrix \( L \) to guarantee \( \lim_{x \to \infty} \| X(k) - \tilde{X}(k) \| = 0 \), where
\[
\begin{aligned}
\tilde{X}(k + 1) &= \begin{bmatrix} G_1 & I \\ 0 & I \end{bmatrix} \tilde{X}(k) + \begin{bmatrix} G(U(k)) \\ 0 \end{bmatrix} + L(Y(k) - \tilde{Y}(k)) \\
\tilde{Y}(k) &= [I \, 0] \tilde{X}(k)
\end{aligned}
\]
(14)
One way to construct the matrix \( L \) is shown as follow.
Since \( G_1 \) is a diagonal matrix, we can set \( L = \begin{bmatrix} L_1 I \\ L_2 I \end{bmatrix} \), then the error system is
\[ \tilde{X}(k + 1) = \begin{bmatrix} G_1 - L_1 I & I \\ -L_2 I & I \end{bmatrix} \tilde{X}(k) = \begin{bmatrix} (g_{1c}^n - L_1) I & I \\ -L_2 I & I \end{bmatrix} \tilde{X}(k) \]

There is no doubt that the matrix \( \begin{bmatrix} (g_{1c}^n - L_1) I & I \\ -L_2 I & I \end{bmatrix} \) has two characteristic roots (denoted as \( \rho_1, \rho_2 \), which are the roots of function (15),

\[ \rho^2 - (1 + g_{1c}^n - L_1)\rho + (L_2 + g_{1c}^n - L_1) = 0 \quad (15) \]

For any given \( \|\rho_i\| < 1 \ i = 1, 2 \), let

\[ \begin{align*}
L_1 &= 1 + g_{1c}^n - (\rho_1 + \rho_2) \\
L_2 &= 1 + \rho_1 \rho_2 - (\rho_1 + \rho_2)
\end{align*} \]

Then the augment system is observable.

**Step 2: Steady states calculation**

The steady states \( x_s \) and steady input signals \( U_s \) can be calculated by solving the following optimization problem

\[ (U_s, x_s) = \arg \min_{U_s, x_s} \left( U_s^T R U_s + (x_s - y_d)^T Q (x_s - y_d) \right) \quad (16) \]

s.t.

\[ \begin{align*}
(I - G_1)x_s - (M_1 + M_2)(A_1 + A_2)U_s &= \hat{O}(k) \\
U_{\min} &\leq U_s \leq U_{\max} \\
y_{\min} &\leq x_s \leq y_{\max}
\end{align*} \]

where \( y_d \) is the target, \( \hat{O}(k) \) is the estimation of unknown offsets, \( P \) and \( Q \) are positive penalty coefficients.

**Step 3: The MPC controller**

At each virtual sampling time and \( x_s \) and \( U_s \) are calculated, to follow the MPC scheme, a finite horizon optimization problem is solved for obtaining the real controller outputs. For \( N \) is the horizon and the solution is recorded as \( \nu_k^* = \{U^*_k, U^*_{k+1} | \cdots | U^*_{k+N-1} | k \} \), the optimization problem is described as

\[ \nu_k^* = \arg \min_{\nu_k^*} \sum_{i=1}^{N} (\delta x_i^T P_i \delta x_i + \delta U_i^T R_i \delta U_i) + \Delta U_k^T Q \Delta U_k \quad (17) \]

Subject to

\[ \begin{align*}
&x(k + j | k) = G_1 x(k + j - 1 | k) + A_2 M_1 U((k + j - 1 - m) | k) \\
&+ (A_2 M_1 + A_1 M_2) U((k + j - 2 - m) | k) \\
&+ (A_2 M_1 + A_1 M_2) U((k + j - 3 - m) | k) \\
&+ \hat{O}(k) \\
&j = 1, 2 \cdots m + N \\
&U_{\min} \leq U((k + j - 1) | k) \leq U_{\max} \\
y_{\min} &\leq x(k + i + m - 1|k) \leq y_{\max}
\end{align*} \]

where

\[ \begin{align*}
\delta x_i &= x(k + i + m - 1|k) - x_s \\
\delta U_i &= U(k + i + 1|k) - U_s \\
\Delta U_k^T &= U(k | k) - U(k - 1)
\end{align*} \]

and \( P_i, R_i \) and \( Q \) are positive definite matrices. Moreover, \( U((k + 1)|k) = U_{k+1} \) if \( l \leq 0 \).

It should be noted that the 3rd item in (17) is introduced to limit too frequent changes in the fuel injection. The punish parameter matrices \( P_i, R_i \) and \( Q \) and horizon length \( N \) are chosen experimentally. Moreover, small \( N \) means simpleness in control law.

4. **TEST BENCH**

The implementation of the proposed control scheme is carried out on a platform developed for ignition-event scale based individual cylinder control. The test bench is constituted by three subsystems, which are a multi-cylinder engine, a dynamometer and a remote control system. The six-cylinder 3.5L car-used SI engine (2GR-FSE) is provided by Toyota Corporation. Since we focus on individual control, excess sensors are equipped, including in-cylinder pressure transducers in all cylinders and Universal Exhaust Gas Oxygen (UEGO) sensors in the right side exhaust manifold and runners. The dynamometer connects with the engine’s crankshaft through a gear-box. It provides additional loads to simulate the road friction effects for the engine under steady operation modes. The remote control system is similar to Hardware In Loop Simulation System (HILS), where a dSPACE real-time control board (ds1103) is employed and it is connected with a PC and the ECU. The hardware system is shown in Fig.3.

5. SIMULATION AND EXPERIMENTAL RESULTS

5.1 Simulation results

For a 6-cylinder SI engine, we construct a simulator for the validation of the controller. The model for simulation is (12) and the parameters are

\[ m = 1, g_1 = 0.3, g_2 = 0.7 \]

\[ A = \begin{bmatrix} 0.65 & 0.2 & 0.15 \\ 0.10 & 0.7 & 0.20 \\ 0.30 & 0.2 & 0.50 \end{bmatrix} \]

\[ O = \begin{bmatrix} -0.04 & 0.05 & -0.03 \end{bmatrix}^T \]
Fig. 5. Data for model identification (Throttle=7deg, speed=2000rpm, load=70Nm)

Fig. 6. Model effects

Fig. 7. Offset free MPC control ($N = 1$, $P_1 = 1$, $R_1 = 1$ and $Q = 50$)
It is clear that condition (11) is satisfied. Let $\rho_1 = 0.2038 < 1$ and $\rho_2 = 0.6232 < 1$, according to (15), we have $L_1 = 1$ and $L_2 = 0.3$. For simplicity, the horizon length is taken as $N = 1$ and the punish parameters in the dynamic optimization (17) is $P_1 = 1$, $R_1 = 1$ and $Q = 5$ in the simulation. The simulation results is shown in Fig.4.

5.2 Experimental results

For real application, it is not necessary to identify matrix $A$ and $M$. The overlap model can be rewritten as (18).

$$\eta_{m_{i}}(k, i) = c \sigma_{m_{i}}(k, 1, i) + \sum_{j=1}^{n} \delta_{ij} \Delta u(3k + i - m - j) + O_{i+1} + \varepsilon$$

where $c$ and $\delta_{ij}$ are parameters determined by matrix $A$ and $M$, which can be identified by LS. Moreover, the pure delay $m$ can be identified by "trail-and-error" method.

In the experiments for identification, the fuel injection is set as pseudo random sequence both in scope and amplitude (Fig.5). 600 sampling data is used for identification and the following 400 sampling data is employed for model validation (the nominal value for fuel injection is $\text{fuel}_{1.35} = 14.1\text{mml/str}$, $\text{fuel}_{2.35} = 15.3\text{mml/str}$). The model is (19) (to show the model effect clearly, the outputs are 15.7 timed in modeling) and the model error is shown in Fig.6. The mean value of the model error at individual sampling BDC point is $-0.0014$, $-0.0014$ and $-0.0020$, the std is 0.0375, 0.0391 and 0.0387.

$$\begin{bmatrix}
0 & 0.5625 & 0 & 0 \\
0 & 0.5753 & 0 & 0.5288 \\
0 & 0.0344 & 0 & 0 \\
0.0429 & 0.0399 & 0 & 0 \\
0.0821 & 0.0551 & 0.0886 & 0 \\
0.0608 & 0.0884 & 0.0926 & 0.0548 \\
0.0660 & 0.1035 & 0 & 0 \\
0.0427 & 0.0305 & 0 & 0 \\
0 & 0.0095 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix} u(l - 3) + \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix} u(l - 4) + \begin{bmatrix}
O_1 & 0 & 0 & 0 \\
0 & O_2 & 0 & 0 \\
0 & 0 & O_3 & 0 \\
0 & 0 & 0 & O_4
\end{bmatrix} + D_i$$

Based on the identified model (19), the experimental results for unknown offset free MPC controller are shown in Fig.7. The first plot of Fig.7 shows the individual fuel injection adjustments from the controller, the third and the fourth plots are mixed A/F value and individual A/F value from lambda sensors. In Fig.7.a, the initial injection command is set at its nominal value (15.3 mml/str). Finally, the controller regulate the F/G at mixing point. Moreover, the individual A/F values are also regulated. In Fig.7.b, an additional fuel injection (0.5 mml/str) is added to cylinder 4, which is compensated by the controller.

It should be noted that the condition (11) can not be validated from model (19). However, from Fig.7, the F/G regulation leads to individual A/F balancing control. In the experiments, consider that the controller will be automatically stopped by the ECU if dramatic change in fuel injection happens, we choose a large positive penalty $Q$ of (17) to avoid this situation. As a result, it takes long time to converge to the new balanced operation (about 20s in Fig.7).

6. CONCLUSION

An overlap model for dynamics from individual fuel injection to F/G at mixing point is developed. Based on the model, a condition is found that if the condition is satisfied then to keep the A/F values sampled at consecutive BDC points from an lambda sensor located at the mixing point can lead to balancing control between cylinders. Moreover, based on this model an unknown offset free MPC controller is designed to eliminate the imbalance between cylinders, where the imbalance is represented as unknown offset in inputs. Finally, the proposed model and controller are validated by simulation and experiments executed in a six-cylinder car-used SI engine.

REFERENCES


