

Air-to-Fuel and Dual-Fuel Ratio Control of an Internal Combustion Engine

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ABSTRACT

Air-to-fuel (A/F) ratio is the mass ratio of the air-to-fuel mixture trapped inside a cylinder before combustion begins, and it affects engine emissions, fuel economy, and other performances. Using an A/F ratio and dual-fuel ratio control oriented engine model, a multi-input-multi-output (MIMO) sliding mode control scheme is used to simultaneously control the mass flow rate of both port fuel injection (PFI) and direct injection (DI) systems. The control target is to regulate the A/F ratio at a desired level (e.g., at stoichiometric) and fuel ratio (ratio of PFI fueling vs. total fueling) to any desired level between zero and one. A MIMO sliding mode controller was designed with guaranteed stability to drive the system A/F and fuel ratios to the desired target under various air flow disturbances. The performance of the sliding mode controller was compared with a baseline multi-loop PID (Proportional-Integral-Derivative) controller through simulations and showed improvements over the baseline controller. Finally, the engine model and proposed sliding mode controller are implemented into a Hardware-In-the-Loop (HIL) simulator and a target engine control module, and HIL simulation is conducted to validate the developed controller for potential implementation in an automotive engine.

INTRODUCTION

Increasing concerns about global climate changes and ever-increasing demands on fossil fuel capacity call for reduced emissions and improved fuel economy. Vehicles equipped with DI fuel systems have been introduced to markets globally. In order to improve DI engine full load performance at high speed, Toyota introduced an engine with a stoichiometric injection

system with two fuel injectors for each cylinder, see [1]. One is a DI injector generating a dual-fan-shaped spray with wide dispersion, while the other is a port injector. The dual-fuel system introduces one additional degree of freedom for engine combustion optimization to reduce emissions with improved fuel economy.

Using gasoline PFI and ethanol DI dual-fuel system to substantially increase gasoline engine efficiency is described in [2]. The main idea is to use a highly boosted small turbocharged engine to match the performance of a much larger engine. Direct injection of ethanol is used to suppress engine knock at high engine load due to its substantial air charge cooling resulting from its high heat of vaporization.

The control of A/F ratio is an increasingly important control problem due to federal and state emission regulations. Operating the spark ignited internal combustion engines at a desired A/F ratio is due to the fact that the highest conversion efficiency of a three-way catalyst occurs around stoichiometric A/F ratio.

There have been several fuel control strategies developed for internal combustion engines to improve the efficiency and to reduce exhaust emissions. A key development in the evolution was the introduction of a closed-loop fuel injection control algorithm [3], followed by a linear quadratic control method [4], and an optimal control and Kalman filtering design [5]. Specific applications of A/F ratio control based on observer measurements in the intake manifold were developed in 1991 [6]. Another approach was based on measurements of exhaust gases by an oxygen sensor and the throttle position [7]. Hedrick also developed a nonlinear sliding mode control of A/F ratio based upon the oxygen sensor feedback [8]. The conventional A/F ratio control for automobiles uses both closed-loop

The control strategies, mentioned above, were mainly for PFI systems. Mitsubishi began to investigate combustion control technologies for direct injection engines in 1996 [9]. Due to the introduction of internal combustion engines with dual-fuel systems (PFI and DI), control of both A/F ratio and fuel ratio (ratio of PFI fueling vs. total fueling) became part of a combustion optimization problem in [10].

This paper is organized as follows. It begins by presenting a simplified A/F and fuel ratio control oriented model, followed by a section that describes an innovative sliding mode controller that regulates both A/F and fuel ratios to desired nonzero targets and simulation results are shown. Next, a state estimator will be presented for a fixed engine operation condition and the HIL environment setup will be described. Finally, HIL simulation results are presented and conclusions are discussed.

The control problem of this work is to vary both fuel mass injection rates ($\dot{m}_{PFI}$ and $\dot{m}_{DI}$) so that the engine A/F ratio is regulated at a desired level (e.g., stoichiometric) and the fuel ratio of effective PFI fueling, $\dot{m}_{PFI_E}$, to total fueling, $\dot{m}_{total} = \dot{m}_{PFI_E} + \dot{m}_{DI}$, is maintained at a desired value as shown in Figure 1. Note that the effective fueling for DI is equal to the injected DI fuel.


$$\dot{m}_{air} = \omega = \omega_0 + \Delta\omega, \quad (1)$$
$$\begin{aligned} x_3 &= A_3 x_3 + B_3 u_3 \\ y_3 &= C_3 x_3 + D_3 u_3, C_3 = [C_3^T \ C_3^T]^T \end{aligned} \quad (8)$$

$$\dot{x}_2 = A_2 x_2 + B_2 \omega \quad (9)$$

$$y_2 = C_2 x_2$$

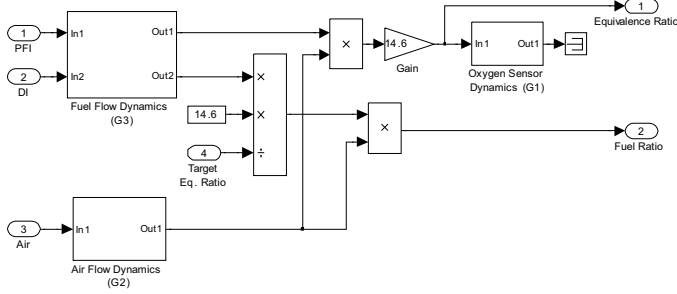


FIGURE 2: EQUIVALENCE AND FUEL RATIO MODEL

The entire system can be expressed by the following state-space model

$$\dot{x} = \begin{bmatrix} A_1 & & \\ & A_2 & \\ & & A_3 \end{bmatrix} x + \begin{bmatrix} B_1 \\ 0 \\ 0 \end{bmatrix} C_2 C_{31} x_3 x_2 + \begin{bmatrix} 0 \\ B_2 \\ 0 \end{bmatrix} \omega + \begin{bmatrix} 0 \\ 0 \\ B_3 \end{bmatrix} u_3 \quad (10)$$

and the output equations for the equivalence and fuel ratios using (10) can be approximated by

$$y_{EqRatio} = 14.6 \cdot C_2 C_{31} x_2 x_3 \quad (11)$$

$$y_{FuelRatio} = 14.6 \cdot C_2 x_2 (C_{32} x_3 + .625 u_1) / \phi_{target} \quad (12)$$

The values for the matrices of the engine model are

$$A_1 = -25; \quad B_1 = 14.6; \quad C_1 = 25;$$

$$A_2 = -5; \quad B_2 = -1; \quad C_2 = 5;$$

$$A_3 = \begin{bmatrix} -20 & 0 & 0.4688 \\ 0 & -20 & 0 \\ 0 & 0 & -1.25 \end{bmatrix}; \quad B_3 = \begin{bmatrix} 0.625 & 0 \\ 0 & 1 \\ 1 & 0 \end{bmatrix};$$

$$C_3 = \begin{bmatrix} 20 & 20 & 0 \\ 0 & 0 & 0.46875 \end{bmatrix}; \quad D_3 = \begin{bmatrix} 0 & 0 \\ 0.625 & 0 \end{bmatrix}.$$

The nonlinear state space engine model must be transformed into the *regular form* [11] below to apply sliding mode control.

$$\dot{\eta} = f_a(\eta, z) + \delta(\eta, z); \quad (13)$$

$$\dot{z} = f_b(\eta, z) + G(\eta, z)u, \quad (14)$$

where the forcing term of equation (13), $\delta(\eta, z)$, contains the disturbance input $\Delta\omega$ and $f_a(\eta, z)$ contains the nonlinear portion of (10). A change of variables,

$$\begin{bmatrix} \eta \\ z \end{bmatrix} = T \cdot x \quad (15)$$

transfers the original state vector,

$$x = [x_1 \quad x_2 \quad x_{31} \quad x_{32} \quad x_{33}]^T \quad (16)$$

into the regular form coordinates, where the transformation matrix T is chosen such that

$$\eta = [x_1 \quad x_2 \quad x_{31} - 0.625 x_{33}]^T \quad (17)$$

$$z = [x_{33} \quad x_{32}]^T \quad (18)$$

Thus, the original system (represented in the regular form) is shown in (19) and (20). It can be seen that the model contains two control inputs corresponding to PFI and DI fueling and one mass air flow disturbance input.

$$\dot{\eta} = \underbrace{\begin{bmatrix} -25 & 0 & 0 \\ 0 & -5 & 0 \\ 0 & 0 & -20 \end{bmatrix} \begin{bmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{bmatrix}}_{f_a(\eta, z)} + \underbrace{\begin{bmatrix} 0 \\ 0 \\ -11.25 \end{bmatrix} z_1 + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}}_{\delta(\eta, z)} h(\eta, z) + \begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix} \delta \quad (19)$$

$$\dot{z} = \underbrace{\begin{bmatrix} -1.25 & 0 \\ 0 & -20 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix}}_{f_b(\eta, z)} + \underbrace{\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}}_G \quad (20)$$

where

$$h(\eta, z) = 1460 \eta_2 (\eta_3 + 0.625 z_1 + z_2).$$

SLIDING MODE CONTROL STRATEGY

Existing sliding mode A/F ratio control applications in [12] and [13] utilized the binary nature of a HEGO (Heated Exhaust Gas Oxygen) sensor to reduce its oscillation resulting from the time delay by using a dynamic, one dimensional sliding surface.

In this paper, a two dimensional sliding surface is selected to control both equivalence and fuel ratios of the dual-fuel system. The sliding surface is defined as

$$s = z - \phi(\eta), \quad (21)$$

where the control objective is to regulate “s” to zero by designing a feedback $\phi(\eta)$ such that it stabilizes equation (19). Letting

$$z = \phi(\eta) = \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} 1.6 \eta_1 \\ -\eta_1 - \eta_3 \end{bmatrix} \quad (22)$$

results in the asymptotic stability at the origin for (19) and decouples the nonlinear dynamics contained in $f_a(\eta, z)$ from the remaining equation. Also, $\phi(\eta)$ does not contain the state η_2 and removes it from having any affect on the system, which is significant because the state η_2 contained the input disturbance, δ . Differentiation of the sliding surfaces yields

$$\begin{aligned} \dot{s} &= \dot{z} - \frac{\partial \phi}{\partial \eta} \dot{\eta} \\ &= f_b(\eta, z) + G(\eta, z)u - \frac{\partial \phi}{\partial \eta} [f_a(\eta, z) + \delta(\eta, z)] \end{aligned} \quad (23)$$

Selecting the control u to cancel the known terms of (23)

$$u = G^{-1}(\eta, z) \left[-f_b(\eta, z) + \frac{\partial \phi}{\partial \eta} f_a(\eta, z) \right] + G^{-1}(\eta, z)v \quad (24)$$

where v is the control input to be defined. Thus,

$$\dot{s} = v - \frac{\partial \phi}{\partial \eta} \delta(\eta, z), \quad (25)$$

and

$$\frac{\partial \phi}{\partial \eta} \delta(\eta, z) = \begin{bmatrix} 1.6 & 0 & 0 \\ -1 & 0 & -1 \end{bmatrix} \begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix} = 0. \quad (26)$$

Therefore (25) becomes

$$\dot{s} = \dot{z} - \frac{\partial \phi}{\partial \eta} \dot{\eta} = v. \quad (27)$$

The selected v needs to force s toward zero and using $V = s^2/2$ as a Lyapunov function candidate for (25) then

$$\dot{V} = s \cdot \dot{s} = s \cdot v \leq |s| \cdot |v|.$$