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Adaptive air-fuel ratio control of dual-injection engines under biofuel blends using extreme learning machine

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ABSTRACT

Dual-injection engines, which allow real-time control and injection of two different fuels, are capable of varying the ratio of biofuel blends at different engine operating conditions for optimal engine performance. However, while many experiments have been carried out on these engines to demonstrate their advantages, very few studies have focused on the corresponding air–fuel ratio (AFR) control strategy. In order to achieve stable engine operation, it is essential to maintain transient AFR during the change of fuel blend ratio. Therefore, this study proposes an adaptive controller for AFR control of dual-injection engines. The proposed controller is designed based on a recently developed machine learning method called extreme learning machine, and its stability is verified with Lyapunov analysis. Simulations have been performed on an industry-level engine simulation software to verify the controller. Since dual-injection engines are not available in the market, a spark-ignition engine has been retrofitted for dual-injection operation so that the proposed controller can be implemented and evaluated experimentally. Both simulation and experiment results show that the proposed controller can effectively regulate the AFR to desired level. The results also show that the proposed controller outperforms the engine built-in AFR controller, indicating its significance for dual-injection engines.

1. Introduction

Increasingly stringent government regulations regarding exhaust emissions of automotive engines and rising concerns over fossil fuel depletion encourage the use of biofuels. The advantages are that biofuels usually generate less pollutants when burnt and can be massively produced with a lower cost. In some countries such as Brazil and United States, bioalcohols and biodiesels have already been widely produced and used as the major alternatives to conventional fuels [1]. Many researches have also been conducted in recent years to study the properties and significances of various types of biofuels [2–6], showing their importance for automotive engines in the near future.

The most general way to use biofuels on engines is to blend them with conventional fuels in the fuel tank or at the gas station before being passed to the fuel line and injected to the engine cylinders. However, in such pre-blend strategy, the blend ratios between the two types of fuels cannot be adjusted dynamically during engine operation. Since most biofuels have different properties than conventional fuels, it is certain that the engine performance can be further improved if the fuel blend ratios can be varied for different operating conditions. A dual-injection strategy for use of biofuels on spark-ignition (SI) engines has therefore been investigated by a number of researchers recently to allow this real-time fuel blend ratio adjustment [7–14]. The idea of this dual-injection strategy is to integrate two sets of injection systems on one single engine so that the amount of the two different fuels and the fuel blend ratios can be controlled instantly and simultaneously according to the engine operating conditions. Such dual-injection strategy can be implemented by using either dual port fuel injection systems or the combination of a direct fuel injection system with a port fuel injection system, as described in [12,13]. Apart from these two ways, in a recent study by Amirante et al. [14], another new real-time fuel mixing strategy was proposed for dual fuels, which, with proper design of the injection lines, can provide precise mixture fractions and satisfactory mixing.

As reported by Daniel et al. [8,9], dual-injection of two fuels can help reduce the fuel consumption and emissions on SI engines as compared to direct injection of pre-blended fuel. Moreover, Liu et al. [15] showed that dual-injection of alcohol-gasoline offers better fuel economy and anti-knock performance. Venugopal et al. [13] also validated through experiments that the brake thermal efficiency and torque can be benefited by varying the fuel ratio at different conditions. All these experimental results have demonstrated the potential of dual-

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injection strategy for using biofuels on SI engines. Nevertheless, while many experiments have been carried out with this strategy, most of the studies only mentioned that the air-fuel ratio (AFR) was kept at stoichiometry; the details on how the two types of fuels are controlled to achieve the desired AFR are rarely discussed. As different fuels have different stoichiometric ratios, the amount of fuel to be injected must be carefully adjusted when the fuel blend ratio is changed. The adjustment of the fuel should also be fast to maintain transient AFR during the change of fuel blend ratio. Hence, design of a reliable and efficient AFR controller for engines with dual-injection strategy is of great interest.

Practically, AFR is controlled by using the combination of feedforward look-up tables and feedback proportional-integral-derivative (PID) controllers. The look-up tables are calibrated to ensure that the engine can maintain operation at different conditions, while the PID controllers compensate the amount of fuel necessary to reach the desired AFR, through the feedback measurement of λ from the oxygen sensors on the exhaust pipe. It has to be noted that λ is a normalized AFR value that is defined as the actual AFR divided by the stoichiometric AFR. It is commonly used for AFR control because the stoichiometric value for λ is always 1 no matter what fuel blend is used. Although PID controllers are quite stable for controlling AFR (or λ) in steady-state condition, the tuning process of the gains is arduous and time-consuming, and the tuned constant gains may not guarantee the control performance in long-term as the λ dynamics may gradually change due to engine aging or variation of operating conditions [16]. Moreover, when the fuel ratio changes (e.g., from 100% gasoline 0% ethanol to 80% gasoline 20% ethanol), the dramatic change in the λ dynamics can be a challenging problem for traditional PID controllers as they are not robust to nonlinearity and uncertainties [17,18]. Considering the limitations of PID controllers, many advanced AFR controllers have been proposed in the past decades (see the recent review by Carbot-Rojas et al. [19]). However, almost none of existing work focuses specifically on the SI engine under dual-injection strategy. The only study focusing solely on AFR control on dual-injection engine is the work by Pace and Zhu [17], who developed a sliding-mode controller (SMC) for both AFR ratio and fuel ratio control of a SI engine under dual-injection strategy. Comparing with a baseline PID controller, the SMC was shown to have better closed-loop response through simulations. The controller was also validated through a hardware-in-the-loop simulator of a mean-value engine model. However, whether it could still perform similarly on a real engine has yet to be proved. The major concern is that SMC requires an analytical model of the engine to derive the control law, but due to the complexity and highly nonlinear nature of engines, an exact engine dynamic model is almost impossible to be derived in reality [16,20,21], and thus un-modeled dynamics may exist that could degrade the performance of the controller in real cases.

In an effort to alleviate the difficulties in identifying the AFR dynamics, the authors of this paper recently employed some machine learning methods to model the AFR dynamics for gasoline injection engines [20,21]. With machine learning methods, the input-output relationship of the AFR dynamics can be determined based on sample data acquired from experiments. Although the models do not possess any significant physical meaning of the engine AFR, they could still achieve better AFR control performance than classical observers. The benefits of using machine learning approaches for engine control have also been verified in [22–24]. However, in most of the previous studies, the AFR models were constructed in advance to the controlling process. That means a large amount of AFR data must be collected on the target engine in prior. Since in this case a dual-fuel engine is considered, the amount of data required for model training would increase exponentially due to the additional parameter of fuel blend ratio. Furthermore, current engine electronic control unit (ECU) has very limited memory and computational speed, so it would be practically difficult to implement those model predictive controllers (MPCs) in the ECU.

Aiming to address the above issues, this paper proposes an adaptive AFR controller for dual-fuel engine based on a machine learning method called extreme learning machine (ELM). ELM is capable of approximating any functions and is very efficient in terms of computational cost. As proved by Huang et al. [25,26], most of the model parameters in ELM can be generated randomly and only part of them has to be tuned to learn the target functions and the resulting model can still retain universal approximation capability. Therefore, by adaptively tuning the parameters of ELM based on the real-time data from the engine, the AFR dynamics of the dual-fuel engine can be learnt online efficiently and thus be controlled simultaneously. Comparing to MPCs, the proposed adaptive controller does not require any prior data in advance and the parameters are only adjusted online, so the memory size and model complexity are greatly reduced, making it more suitable for practical implementation. In order to guarantee the stability of the closed-loop control system, the tuning law of the parameters in this paper is derived based on Lyapunov theory instead of the least-squares method used in original ELM, and the corresponding stability analysis is also provided in this paper. In addition, a well-tuned engine built-in PID-based AFR controller is also employed and compared with the proposed controller to evaluate its significance.

In a nutshell, this paper is novel in the following aspects: (i) a new design of AFR controller for dual-injection engines under biofuel blends; (ii) a novel adaptive control algorithm based on Lyapunov stability theory; and (iii) a comparison among the proposed controller and the conventional PID controller for AFR control in both simulations and experiments.

2. Controller design

2.1. Theories and problem formulation

Theoretically, the λ value for a blend of two distinct fuels is expressed as:

$$\lambda = \frac{m_{\mathrm{a}}}{r m_{\mathrm{f}} \rho_1 \mathrm{AFR}_{\mathrm{s1}} + (1-r) m_{\mathrm{f}} \rho_2 \mathrm{AFR}_{\mathrm{s2}}} \tag{1}$$

where m_{a} and m_{f} are the mass of air and the total mass of the blended fuel, r is the volumetric ratio between the two fuels, ρ_1 and ρ_2 are the densities of the two fuels, and $\mathrm{AFR}_{\mathrm{s1}}$ and $\mathrm{AFR}_{\mathrm{s2}}$ are the stoichiometric AFR of the two fuels respectively. Thus, for a desired λ (denoted as λ_{des}), the required total mass of the blended fuel can be calculated by:

$$m_{\mathrm{f}} = \frac{m_{\mathrm{a}}}{\lambda_{\mathrm{des}} [r \rho_1 \mathrm{AFR}_{\mathrm{s1}} + (1-r) \rho_2 \mathrm{AFR}_{\mathrm{s2}}]}. \tag{2}$$

In practice, however, it is very difficult to directly measure the intake air mass due to the complicated geometry of intake manifold and the presence of uncertainty in air dynamics. Moreover, the densities of the fuels are also very difficult to precisely obtain because they vary with temperature, humidity and pressure, etc. Therefore, direct use of Eq. (2) for regulating λ to the desired value is infeasible. To deal with this issue, the λ dynamics of the dual-injection engine system can be described using the following affine nonlinear discrete-time system:

$$y_{k+1} = g(\boldsymbol{x}_k) + \varphi(\boldsymbol{x}_k) u_k + \gamma(\boldsymbol{x}_k) \theta_k + \alpha(\boldsymbol{x}_k) r_k + \xi_k \tag{3}$$

where $g(\cdot)$, $\varphi(\cdot)$, $\gamma(\cdot)$ and $\alpha(\cdot)$ are four bounded smooth nonlinear functions, $\boldsymbol{x}_k = [y_k, y_{k-1}, \ldots, y_{k-n+1}, u_{k-1}, u_{k-2}, \ldots, u_{k-m+1}, \theta_{k-1}, \theta_{k-2}, \ldots, \theta_{k-m+1}, r_{k-1}, r_{k-2}, \ldots, r_{k-m+1}]$ is the state vector, y is the system output (i.e. λ), u is the total mass of the two distinct fuels (i.e., m_{f}), θ is the throttle position, r is the fuel blend ratio, ξ represents the system uncertainties and external disturbances, k is the time step, and $m \leqslant n$ are the system order. Note that u, θ and r are the three controllable parameters of the engine system.

In this system, both the amount of intake air and the densities of the fuels are omitted as compared to Eq. (2), because they can already be reflected by the throttle position and the trend of λ time-series. Then, in order to match the characteristics of λ, the following assumptions about the system are made: