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Air-Fuel Ratio Regulation with Optimum Throttle Opening in Diesel-Dual-Fuel Engine

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ABSTRACT

Accurate air-fuel ratio control is required for good engine performance and low emission in diesel dual fuel engine. Two actuators directly affect the ratio are the air throttle and the EGR valve. Maximum air throttle opening is favorable to minimize pumping loss, and the EGR valve opening should follow closely the values in a well-tuned map to minimize emission. In the past, the two actuators were either controlled separately or simultaneously to achieve the air-fuel ratio set point without much consideration on the actuators' opening positions. We proposed a logic that alternated between actuating the air throttle and the EGR valve to maintain optimum air throttle opening. Since each actuator was controlled one at a time, the overall control system was simplified, yet any advanced controller could be applied to increase the accuracy of each actuator. Experiments on four-cylindrical diesel-dual-fuel engines showed that the air throttle opening was optimized at all time, whereas the EGR valve opening followed closely the values in a well-tuned map. The air-fuel ratio was also accurately regulated with widest range possible. Both new-European-driving-cycle and set point changes tests were performed on engine and chassis dynamometers, which demonstrated the effectiveness of the proposed method.

INTRODUCTION

Converting existing diesel pick-up trucks into diesel-dual-fuel (DDF) trucks, in which compressed natural gas (CNG) is used as primary fuel and diesel is used only as secondary fuel, has recently obtained more interest from the industries. With an aim of using CNG by 50-70 percentages by energy, the DDF engine should have lower fuel cost and possibly higher output power than the diesel engine.

Air-loop control of the DDF engine is more important and challenging than that of the gasoline engine, diesel engine, and gasoline with CNG engine. Because the CNG is mixed with air prior to entering the cylinders and diesel is used in a significantly less amount, without the assistance from spark plugs, proper combustion heavily relies on correct air-fuel ratio. Hence, accurate control of the air-fuel ratio becomes a necessity. Our experiences with the DDF engines have shown that poor air-fuel ratio control, especially during transient operations, results in excessive knocks and emissions.

Air-fuel ratio control of the DDF engines is challenging due to several reasons. First, the control system involves two actuators, namely throttle and EGR valve. The control problem has two inputs, which are the throttle and EGR valve openings, and one output, which is the air-fuel ratio. As is traditional in multi-variable control problem, the interactions between throttle and EGR valve complicate the control design. For example, one air-fuel ratio value can be obtained from various combinations of the throttle and EGR valve openings. To reach a desired air-fuel ratio, the movement of one actuator can also affect the other actuator. Second, it is normally difficult to obtain accurate plant model since every factors in running the engine seems to affect the air path. Detailed model obtained from CFD or first principles is usually too complex to be used in control design. The controller therefore should be either model-free or tolerant of the model uncertainty. Third, because air and gas mixture is compressible, fluid wave acts as external disturbance to the system. Fourth, especially during transient operations, the air-fuel ratio calculated from intake air measurement may not represent actual air inside the cylinder that directly affects combustion. Other challenges come from noise of air-flow sensor, time delay resulting in non-minimum phase plant, nonlinearity, and variety of operating points.

Existing publicly available literature does not contain much work pertaining to the air-fuel ratio control of the DDF engine. Some closely related work is as follows. Ref. [1] applied dynamic feedback linearization based on the property of flatness to regulate air-fuel ratio of a diesel engine by controlling variable geometry turbocharger and EGR valve. Ref. [2] used fuzzy control to design an air-fuel ratio tracking controller for a diesel engine. The fuzzy logic was used to represent uncertain plant, from which controller was designed. Ref. [3] applied backstepping control with augmented integration. Ref. [4] used advanced dynamic modeling and system identification techniques to control the air-fuel ratio by adjusting the solenoid gas injectors using lambda feedback.

Some work involves designing an observer to estimate actual air inside the cylinder. Ref. [5] designed an intake-air observer from a Takagi-Sugeno fuzzy neural network. The observer estimated fresh air entering the cylinder. A coordinated EGR-VGT controller was designed based on the observer. Ref. [6] developed an air-fuel ratio estimator for each cylinder from a measurement by a sensor located downstream the turbine. The information was used with a simple PI controller to balance the air-fuel ratio of each cylinder. Ref. [7] used throttle angle information in predictive air mass flow rate estimation to achieve finer air-fuel ratio control during transients. The information is useful because, during transient operations, the air mass flow varies largely from fast throttle opening and closing actions. Ref. [8] contained a real-time state observer for in-cylinder oxygen mass estimation and a mode-switching controller forming an airflow-dominant control system.

In this paper, we propose a switch-and-hold logic, which was designed to optimize the throttle opening, hence, minimize pumping loss. Either the throttle or the EGR valve is actuated at a time to solve the actuators' interaction problem. By reducing the problem to single-input-single-output, controllers for the throttle and EGR valve can be designed separately, which opens more rooms for more advanced control techniques. Nevertheless, in our case, two PID controllers were used in the control system because they are popular, are well understood, possess an acceptable amount of robustness, conveniently incorporate some modifications such as gain scheduling, and do not require plant model.

Ref. [9] also presented a similar work, but instead of throttle, the VGT was actuated together with the EGR valve to control oxygen-to-fuel ratio and EGR fraction of diesel engine. Both actuators were designed to minimize pumping loss, which was defined to be the difference between exhaust manifold and intake manifold pressures. However, since the control system had two inputs and two outputs, and no attempt was made to reduce the problem to single-input-single-output, the interaction between the two actuators resulted in a less-than-optimum pumping-loss-reduction algorithm.

As in most actuators, both throttle and EGR valve have deadzone and hysteresis. Although small, these hard nonlinearities can result in poor actuator control, especially at small opening angles. Since throttle should not be fully closed, it is necessary to be able to put a lower limit for the throttle opening in the control algorithm. In using the air-fuel ratio tracking error to drive the throttle directly, we found that it was difficult to implement a lower limit for the throttle opening because limiting the PWM control effort sent to the throttle did not guarantee that the throttle will not be fully closed due to those hard nonlinearities.

A modification was proposed such that, instead of using the air-fuel ratio tracking error to drive the throttle and EGR valve directly, the tracking error was first converted to desired opening angles from which the throttle and EGR valve were commanded to follow. By this way, a lower limit can easily be placed on the desired opening angles.

The content of this paper is divided into four sections, which are introduction, control system design, experimental results, and conclusions. We have presented the introduction in this section. In control system design section to follow, we present the switch-and-hold logic and the overall air-fuel ratio control algorithm including its modification. Then, in the experimental results section, various implementation results on a pick-up truck and an engine test bed are presented. The paper is closed with a conclusions section followed by all the necessary back matters.

CONTROL SYSTEM DESIGN

Figure 1 is a simplified diagram of an air-path system in typical diesel engine with the addition of a mass-air-flow (MAF) sensor to measure intake air mass. The intake air mass signal is sent to the electronic control unit (ECU) to calculate the air-fuel ratio and to compute control efforts for throttle and EGR valve. The throttle allows fresh air to come into the engine, whereas the EGR valve permits part of the exhaust gas (EG) to circulate through the engine as exhaust gas recirculation (EGR.) In making of diesel-dual-fuel engine, typical diesel engine is modified to inject the CNG at the intake ports of each cylinder (not shown in Figure 1.)

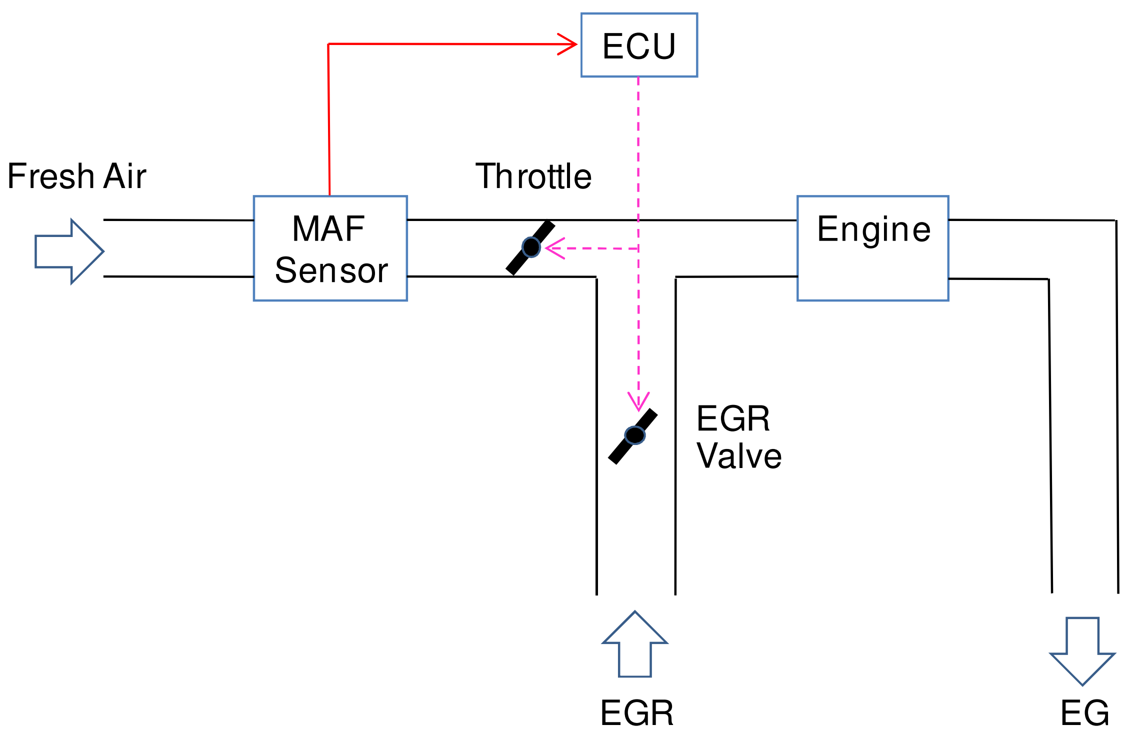

Figure 1: Air-path system with pertaining sensors and actuators.

Our air-fuel ratio is computed according to the formula

$$\lambda = \frac{(A/F)_{actual}}{(A/F)_{stoi}} = \frac{\left(\frac{A}{F_g + F_d}\right)}{R(A/F)_g + (1-R)(A/F)_d}, \tag{1}$$

where λ is the air-fuel ratio, A is quantity of air actually used, F_g is quantity of CNG actually used, F_d is quantity of diesel actually used, R is replacement ratio, which is the ratio between the CNG mass and total fuel mass, $(A/F)_g$ is a constant equals 16.3, and $(A/F)_d$ is a constant equals 14.6.

Desired air-fuel ratio λ_d was obtained as a map from engine speed in rpm and load, which is represented by the indicated mean effective pressure (IMEP.) Figure 2 shows the map of our DDF engine, tuned for good performance and low emissions. The desired air-fuel ratio ranges from 1.3 during medium load to 1.5-1.6 during very high and low load. This is contrary to the SI engine, where the desired air-fuel ratio is fixed at a value, and to the CI engine, where throttle is normally opened fully. The map clearly indicates the need for a good control algorithm to regulate the actual air-fuel ratio.

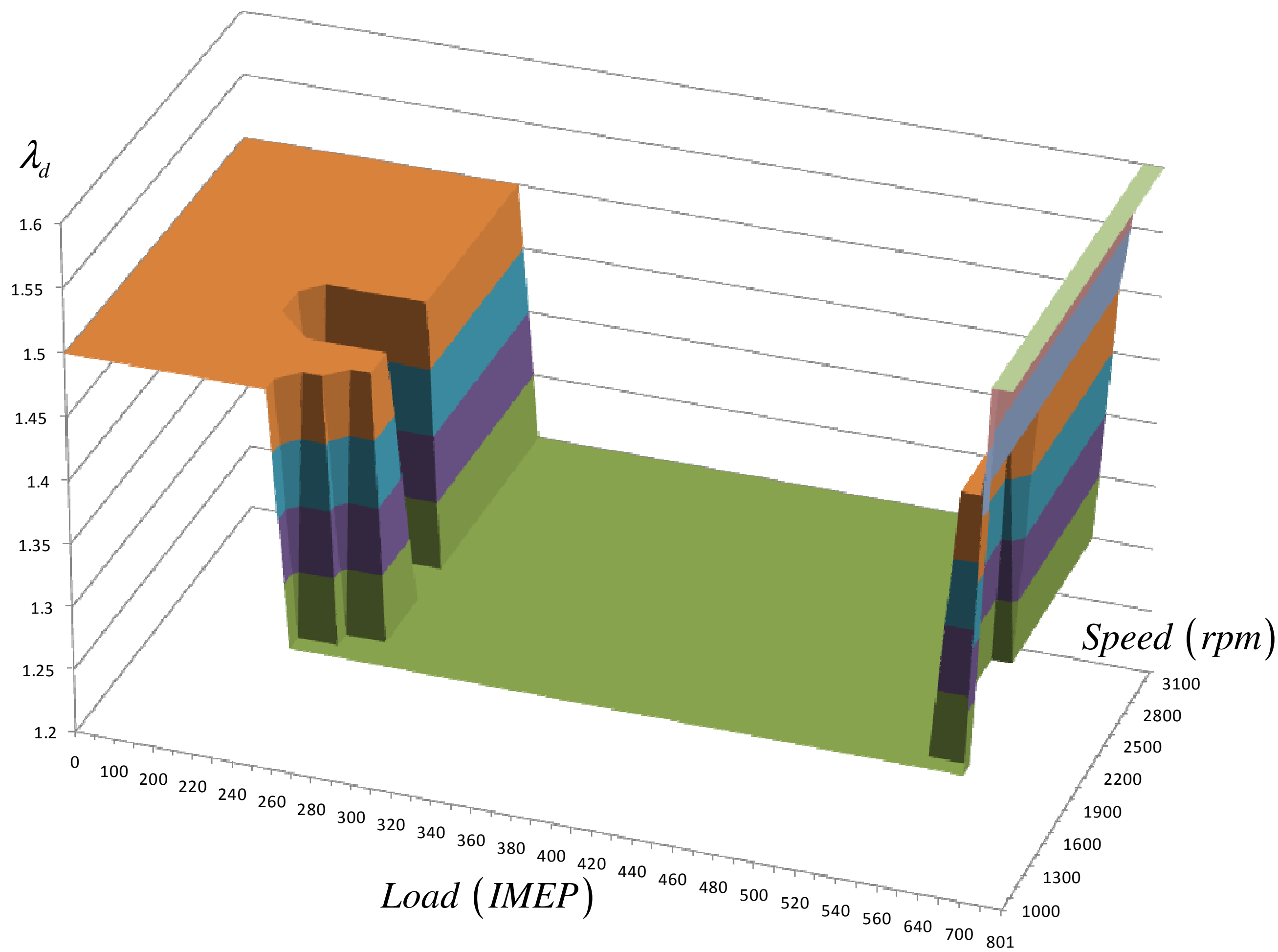

Figure 2: Map of the desired air-fuel ratio as a function of engine speed (rpm) and load (IMEP).

Because the throttle directly affects the amount of air used A in (1), it is clear that the amount of the throttle opening is proportional to the air-fuel ratio, that is, increasing throttle opening increases the air-fuel ratio and decreasing throttle opening decreases the air-fuel ratio. However, it is less clear that the amount of the EGR valve opening is inversely proportional to the air-fuel ratio. Increasing EGR opening decreases the air-fuel ratio, and decreasing EGR opening increases the air-fuel ratio. The EGR valve affects the air-fuel ratio (1) via the amount of fuel used.

For pumping loss minimization, we aim to optimize the throttle opening, that is, to open the throttle as much as possible at all times. The optimum movement of the throttle and the EGR valve depend on current EGR valve position and current throttle position (TPS.) Table 1 contains the logic in moving the EGR valve and the throttle to achieve desired air-fuel ratio.

Notice that, in increasing the air-fuel ratio, higher priority is given to increasing the throttle opening. The EGR valve opening is decreased only after the throttle is opened fully. Maximum achievable air-fuel ratio occurs when the throttle is at maximum opening and the EGR valve is at minimum opening.

In decreasing the air-fuel ratio, we choose to increase the EGR valve opening first before decrease the throttle opening. This is to maintain the throttle opening as wide as possible. Minimum achievable air-fuel ratio occurs when the throttle is at minimum opening and the EGR valve is at maximum opening.

Table 1: Logic in moving EGR valve and throttle to achieve desired λ.

Increasing λ			Decreasing λ		
Current EGR Position	Current Throttle Position (TPS)	Action	Current EGR Position	Current Throttle Position (TPS)	Action
Max	Max	Decrease EGR	Max	Max	Decrease TPS
Max	Middle	Increase TPS	Max	Middle	Decrease TPS
Max	Min	Increase TPS	Max	Min	Minimum λ
Middle	Max	Decrease EGR	Middle	Max	Increase EGR
Middle	Middle	Increase TPS	Middle	Middle	Increase EGR
Middle	Min	Increase TPS	Middle	Min	Increase EGR
Min	Max	Maximum λ	Min	Max	Increase EGR
Min	Middle	Increase TPS	Min	Middle	Increase EGR
Min	Min	Increase TPS	Min	Min	Increase EGR

Figure 3 contains two diagrams showing the logic in Table 1. Figure 3(a) is for increasing the air-fuel ratio, and Figure 3(b) is for decreasing the air-fuel ratio. Two X symbols mark actuator positions where minimum and maximum achievable air-to-fuel ratios are obtained. As an example, suppose the current EGR valve and throttle openings are in the middle, and we would like to increase the air-fuel ratio, the throttle opening would be increased first, until maximum position is reached, then the EGR valve opening would be decrease, until minimum position is reached. Only then the maximum achievable air-fuel ratio is obtained for that engine operating conditions and nothing else can be done to increase the ratio further.

Following the logic above, we devised an overall air-fuel ratio control system that chooses to actuate either the throttle or the EGR valve at a time. Figure 4 contains a diagram of the proposed control system, where λ is the actual air-fuel ratio computed on-line using (1), λ_d is the desired air-fuel ratio obtained on-line from the map in Figure 2, e is the tracking error, G_T and G_E are controllers for the throttle and the EGR valve whose outputs are u_T and u_E respectively, P_T and P_E represent the throttle and the EGR valve whose position outputs are θ_T and θ_E respectively. The measured output positions θ_T and θ_E are fed back to the switch-and-hold algorithm together with the tracking error e. The output from the switch-and-hold algorithm determines which actuator to be actuated.

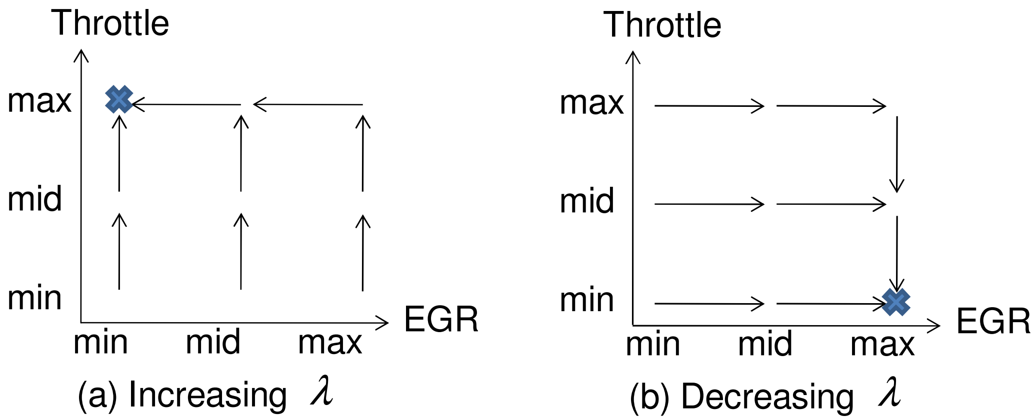

Figure 3: Desirable movements of the air throttle and EGR valve in increasing and decreasing the air-fuel ratio.

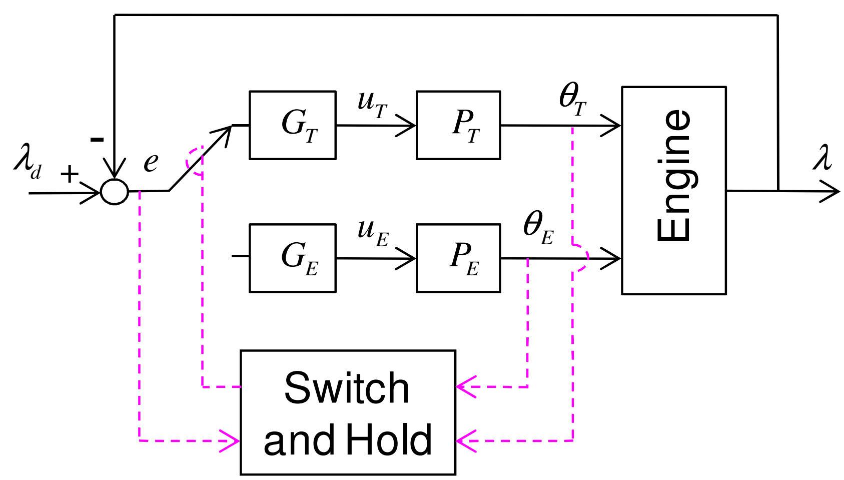

Figure 4: Overall air-fuel ratio control system with switch-and-hold logic.

Following the logic in Figure 3, the switch-and-hold algorithm is as follows. The throttle is actuated and the EGR valve is held constant when either one of these happens:

1) $\lambda_d - \lambda > 0$ (must increase λ) and the throttle opening is not at maximum.

2) $\lambda_d - \lambda < 0$ (must decrease λ) and the EGR valve opening is at maximum.

Or the EGR valve is actuated and the throttle is held constant when either one of these happens:

3) $\lambda_d - \lambda > 0$ (must increase λ) and the throttle opening is at maximum.

4) $\lambda_d - \lambda < 0$ (must decrease λ) and the EGR valve opening is not at maximum.

Note that the logic in 1) corresponds to the vertical lines in Figure 3(a), the logic in 2) corresponds to the vertical line in Figure 3(b), the logic in 3) corresponds to the horizontal line in Figure 3(a), the logic in 4) corresponds to the horizontal lines in Figure 3(b). Since the logic 1) and 2) are opposite of 3) and 4), either 1) and 2) or 3) and 4) need to be put in the software code to implement the algorithm.

One advantage of the set-up in Figure 4 is that, because the tracking error e directly drives the throttle and the EGR valve, the control system is very active and can respond swiftly to the driver especially during transient operations. However, one disadvantage is that it is difficult to set a lower limit for the throttle opening. Normally, the throttle should not be fully closed to avoid high emission. Because of actuator's backlash and hysteresis and varying operating points, setting a constant lower limit at u_T does not always guarantee that the throttle will not be fully closed.

To avoid this problem, a modification to the control system in Figure 4 was devised. Figure 5 contains this modification. Instead of being passed directly to the controllers G_T and G_E, the tracking error e is now used to create reference values θ_{TR} and θ_{ER} for the throttle and the EGR valve to follow. K_1 and K_2 are two positive constant gains, which can be of different values. G_T and G_E are two separated controllers to ensure that the throttle opening θ_T and the EGR valve opening θ_E track their reference values θ_{TR} and θ_{ER} closely.

The reference values θ_{TR} and θ_{ER} are initially at fully opened (100%). As an example to demonstrate how this modified algorithm works, suppose first that the tracking error is less than zero, then there will be a need to decrease the air-fuel ratio. Since the EGR valve is already at fully opened, the switch-and-hold logic will choose to actuate throttle and the quantity K_1e will be added to the 100% reference position to be θ_{TR}. The negative K_1e will result in decreasing the throttle opening. Suppose then that the tracking error now is greater than zero, there will be a need to increase the air-fuel ratio. The now positive quantity K_1e will result in increasing the throttle opening. After the throttle is fully opened, if the error is still greater than zero, the switch-and-hold algorithm will choose to exercise the EGR valve. The throttle will be held at 100%, and the negative quantity $-K_2e$ will result in decreasing the EGR valve opening. This cycle will go on ensuring the good tracking of the air-fuel ratio with optimum throttle opening.

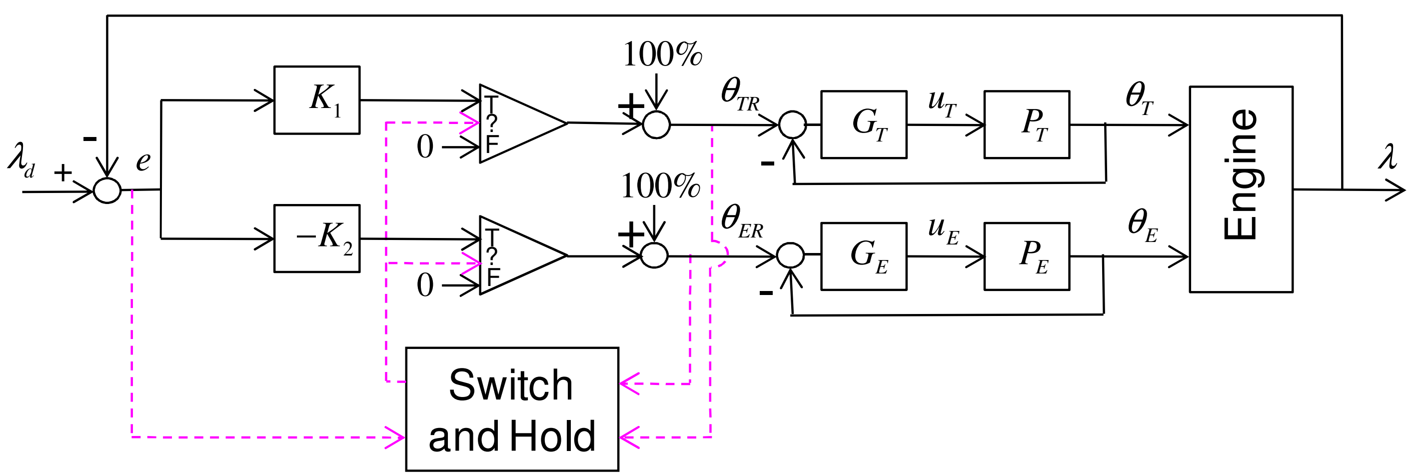

Figure 5: Modified air-fuel ratio control system.

EXPERIMENTAL RESULTS

We implemented the control algorithm in Figure 4 and the modified control algorithm in Figure 5 to an engine test bed and a pick-up truck using the same engine model. The engine test bed was connected to an engine dynamometer, and the pick-up truck was connected to a chassis dynamometer. The engine was modified from a Toyota 2KD-FTV diesel engine to run diesel-dual-fuel by injecting 375 kPa CNG to each of the four intake ports. The distance from the CNG injector to the port is kept as small as possible at 25 cm to reduce time delay.

The engine has four cylinders, each of 2.5 liters, sixteen intake and exhausted valves with double overhead cam shaft (DOHC), a turbocharger with an EGR valve and a throttle but without variable geometry turbine (VGT), and common-rail direct fuel injection system.

The OEM ECU was replaced with an ECU whose hardwares are mainly from National Instruments. All control algorithms were written in Labview graphical programming language. A desktop computer acts as a host to communicate with human operator and is connected to a target running Labview Realtime and FPGA modules.

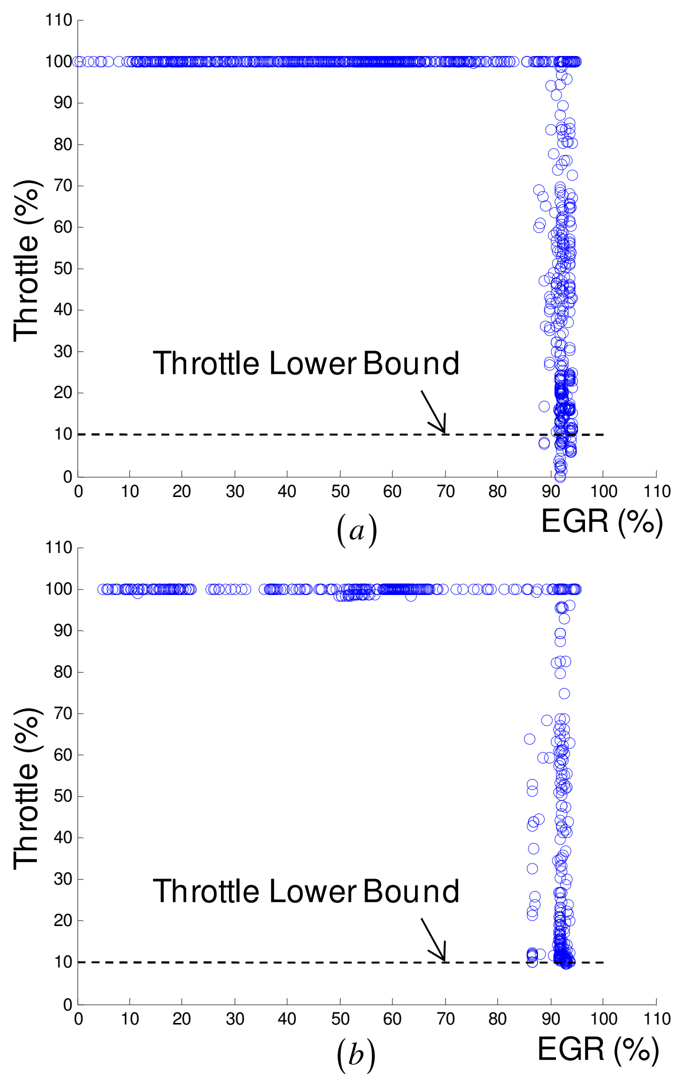

Figure 6: Movements of the throttle and EGR valve recorded from a pick-up truck during a European driving cycle. (a) Using the algorithm in Figure 4. (b) Using the modified algorithm in Figure 5.

For simplicity two simple PID controllers were used as G_T and G_E for both algorithms in Figure 4 and Figure 5. However, the PID controllers can easily be replaced by more advanced controllers, which might improve the tracking performance further. All the PID gains and the positive constants K_1 and K_2 were chosen from trial-and-error.

We first discuss the experimental results from the pick-up truck, followed by the results from the engine test bed. The pick-up truck was commanded to follow the new European driving cycle (NEDC.) The whole cycle comprises four urban cycles, each of about 200 seconds, and a sub-urban cycle of about 500 seconds.

In following the NEDC, Figure 6(a) shows the throttle opening percentage versus the EGR valve opening percentage for the case when the control algorithm in Figure 4 was implemented. The throttle and the EGR valve both operated at their optimum values as expected. It should be noted that since our initial throttle and EGR valve openings were set at fully opened (100%) or at the top-right corner. According to the switch-and-hold algorithm, the throttle and EGR valve positions will never leave their top horizontal line and right vertical line. Notice also that some of the throttle openings were lower than the lower bound, which is a disadvantage mentioned earlier of this algorithm. The fully closed throttle resulted in high emissions and should be avoided.

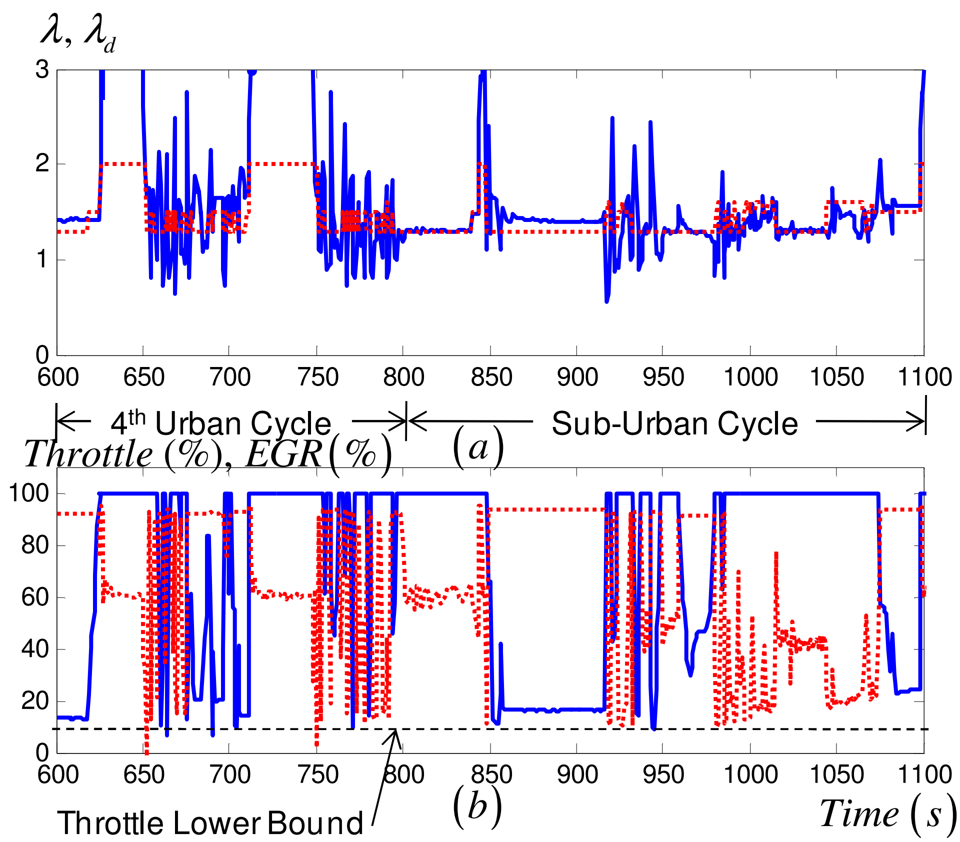

Figure 7: Fourth urban cycle and sub-urban cycle in the NEDC test on a pick-up truck, using the algorithm in Figure 4. (a) Actual lambda (solid line) and desired lambda (dash line.) (b) Throttle opening percentage (solid line) and EGR valve opening percentage (dash line.)

In Figure 6(b), the modified algorithm was implemented. We were able to enforce a lower bound on the throttle opening at all times by inputting a limit directly at the desired throttle opening θ_{TR}. At the same time, more deviations of the throttle and the EGR valve openings can be seen around their maximum values. This is because the tracking error was not used to drive the actuators directly but was converted as reference values for the PID controllers to follow. The tracking error by the PID contributes to the more deviations seen.

Figure 7 contains the tracking results from following the NEDC of the pick-up truck using the algorithm in Figure 4. Figure 7(a) shows the plots of the measured air-fuel ratio λ (in solid line) and the desired air-fuel ratio λ_d (in dash line.) Both are plotted versus time. Since similar tracking results were obtained for all four urban cycles, for clarity of presentation, only the results of the fourth urban cycle and the sub-urban cycle are presented. Figure 7(b) shows the plots of the throttle opening percentage (in solid line) and the EGR valve opening percentage (in dash line) versus time.

In Figure 7, there are some intervals that the measured air-fuel ratio does not follow the desired air-fuel ratio closely, for example, during 630 to 650 and 715 to 750 seconds. This is because, during these intervals, the engine mode was temporarily switched to use only diesel fuel for low load and the air-fuel ratio was temporarily not regulated. The measured air-fuel ratio was able to follow the desired air-fuel ratio closely with the exceptions of some points, for example, at around 610, 850 to 920, and 1050 seconds, where both actuators reached their physical limits. The throttle opening occasionally fell below the lower bound as can be seen at 660 and 690 seconds. High emissions could be seen during these periods.

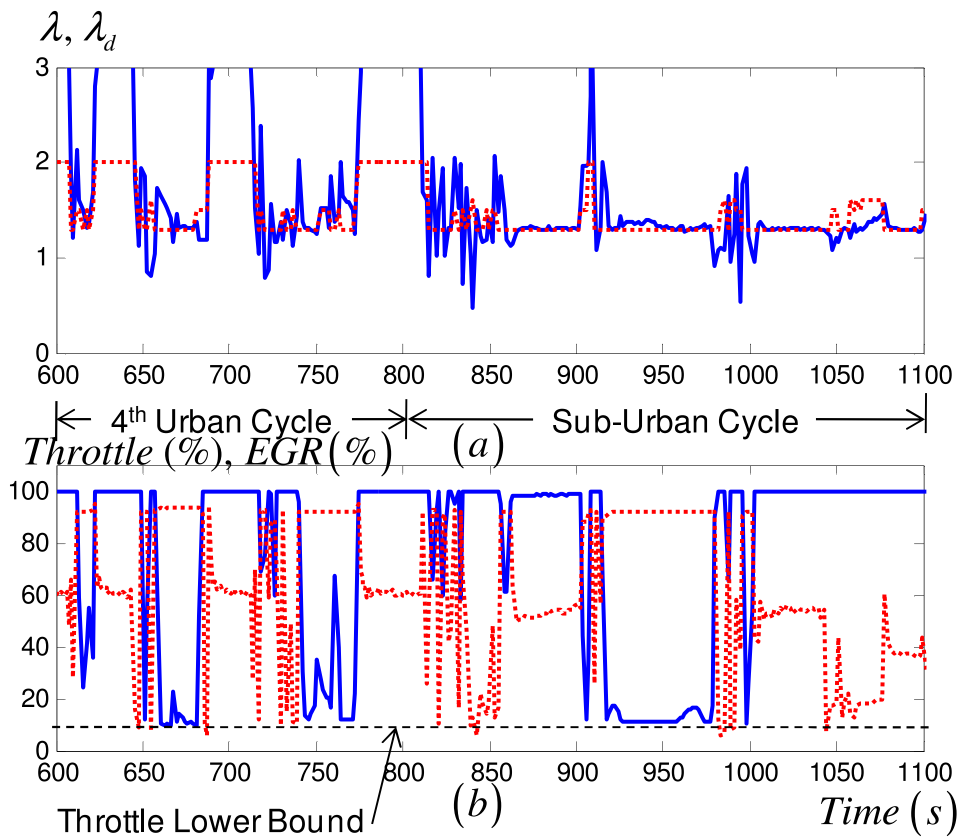

Figure 8: Fourth urban cycle and sub-urban cycle in the NEDC test on a pick-up truck, using the modified algorithm in Figure 5. (a) Actual lambda (solid line) and desired lambda (dash line.) (b) Throttle opening percentage (solid line) and EGR valve opening percentage (dash line.)

Figure 8 presents similar data to that of Figure 7, but it contains the results on implementing the modified algorithm in Figure 5. Figure 8(b) clearly shows that no throttle opening went below the lower bound, which is what the modified algorithm tends to accomplish. By comparing Figure 8(a) with Figure 7(a), we can see that the measured lambda is less fluctuated in Figure 8(a), which is a result of less active throttle and EGR valve as can be seen in Figure 7(b) and Figure 8(b). The modified algorithm has less active actuators because the tracking error is not used to drive the actuators directly but through reference inputs.

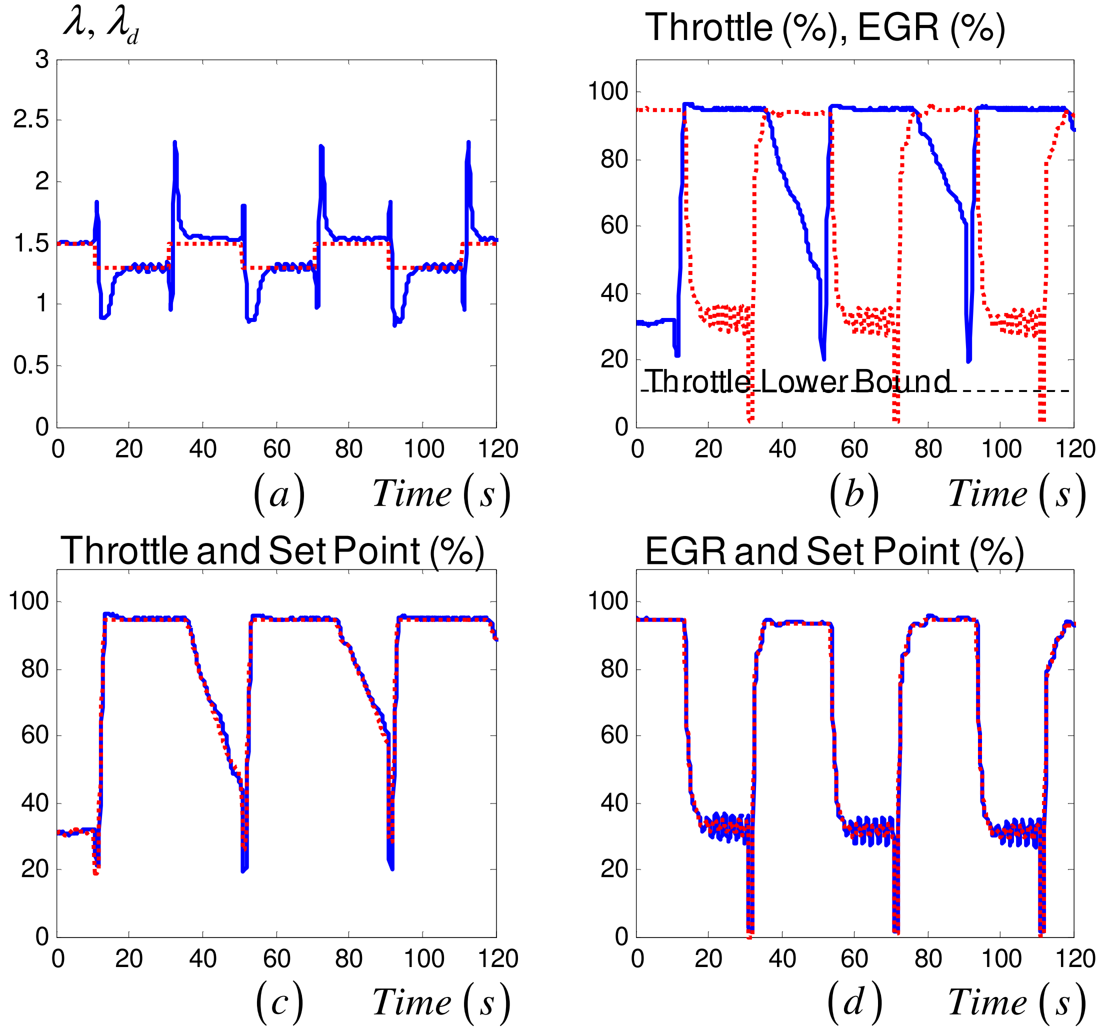

Figure 9: Set point changes test on an engine test bed. (a) Actual lambda (solid line) and desired lambda (dash line.) (b) Throttle opening percentage (solid line) and EGR valve opening percentage (dash line.) (c) Throttle opening percentage (solid line) and its set point (dash line.) (d) EGR valve opening percentage (solid line) and its set point (dash line.)

Figure 9 includes the experimental results from the engine test bed using the modified algorithm in Figure 5. The measured air-fuel ratio λ was commanded to follow step changes in the desired air-fuel ratio λ_d. Figure 9(a) contains plots of the measured air-fuel ratio (in solid line) and the desired air-fuel ratio (in dash line) versus time. The measured air-fuel ratio was able to follow the desired air-fuel ratio well, especially at steady state. The response shows that the system has non-minimum phase, which can be seen from initial wrong direction of the measured air-fuel ratio in following the step changes of the desired air-fuel ratio. As a result of time delay commonly seen in applications involving gas flow, this non-minimum phase can hinder the control system if not dealt with. Figure 9(b) shows the throttle opening percentage (in solid line) and the EGR valve opening percentage (in dash line.) Both actuators operated as expected with the throttle opening well above the lower bound. The EGR valve opening was chattering, which is a result of too high K_2 gain. Figure 9(c) shows plots of the desired throttle opening θ_{TR} (in dash line) and the measured throttle opening θ_T (in solid line) versus time. The throttle was able to follow its desired values closely using only a simple PID. This is because the throttle is operated in gaseous condition, which should not be difficult to control its position. Figure 9(d) contains plots of the desired EGR valve opening θ_{ER} (in dash line) and the measured EGR valve opening θ_E (in solid line) versus time. The EGR valve was also able to follow closely its desired values.

CONCLUSIONS

Two control algorithms are presented to regulate the air-fuel ratio of diesel-dual-fuel engine. Based on the design of a switch-and-hold logic, either throttle or EGR valve is exercised at a time separating the multi-variable problem into two single-variable problems, which can be more easily handled. The logic was designed to keep the throttle open as much as possible to reduce pumping loss. Experiments on a pick-up truck and a test bed, whose engines were converted to run diesel-dual-fuel, have shown the effectiveness of the algorithms. The modified algorithm is superior in that it can prevent the throttle opening from going below a specified lower limit to avoid high level of emissions. We also found that the actuators were not overly active using the modified algorithm.

There are several possible research directions. First, because the amount of fuel used also affects the air-fuel ratio, regulating the injection duration to help control the air-fuel ratio should be explored. One advantage is that the fuel regulation should have faster dynamic than the air regulation. Second, one should look into the interactions between the throttle and the EGR valve and possibly form a full multi-variable problem, which can be solved using techniques such as H_∞ control. Even though the throttle opening directly affects the air-fuel ratio, the effect from the EGR valve opening is not quite obvious. Instead of tiring the EGR valve opening to the air-fuel ratio, another factor such as EGR fraction may be used as a result of changing the EGR valve opening in the multi-variable setting. Third, the non-minimum phase presented in the air-path system should be dealt with to obtain better tracking accuracy, especially during transient operations. Fourth, since the air-fuel ratio obtained from MAF signal is not exactly the amount of air in the cylinder that creates combustion, an observer should be investigated in estimating the air trapped in each cylinder for the DDF engine.

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