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A method of lean air–fuel ratio control using combustion pressure measurement

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Abstract

In this paper a method for control of air–fuel ratio (AFR) in cold or lean-burning spark-ignited engines is investigated. The technique uses combustion pressure as measured by a cylinder-mounted sensor, and is based on the phenomenon of increasing cycle-to-cycle combustion pressure variation as the air–fuel mixture approaches the limits of flammability. The cylinder pressure is measured from one engine cycle to the next, and large drops in mean effective pressure (IMEP) are used as an indicator of poor combustion. In response, the airflow or fuel flow to the engine can be manipulated. In a series of experiments, the air and fuel are alternately investigated as control inputs, and performance compared. The resulting control system is a high-bandwidth AFR control strategy that can be used under cold or lean conditions when conventional exhaust gas oxygen sensor cannot be used. Moreover, the method is directly tied to the combustion process and the relevant performance measure — combustion stability — that is perceptible to the driver as a rough-running engine.

1. Introduction

This work is concerned with hydrocarbon emissions reduction in spark-ignited engines. This is the number one problem with emissions from today's vehicles and the one that has so far been the most intractable. The cold start period, typically the first 2–3 min of engine operation, is the phase of engine operation mostly responsible for the emission of hydrocarbon pollutants. During this time the catalytic converter is ineffective at oxidizing hydrocarbons due to its low temperature. Also a lack of sensing make proper fueling difficult. The open-loop fueling is necessarily conservative on the side of excess fuel, to prevent stalling of the engine from weak mixtures due to poor fuel evaporation. This part of the control strategy calibration for production vehicles requires a great deal of effort to properly trade off emissions with driveability aspects such as smooth power production and steady idle. An effective means for reducing hydrocarbon emissions from spark-ignited engines when the catalyst is not operational would be to operate with excess air.

In this paper, we investigate a closed-loop control scheme to achieve lean-limit operation of a spark-ignited engine. The objective is to move the engine operating point to a more lean condition, while maintaining a predefined level of engine roughness. We compare the effect of airflow and fuel flow as actuators in the closed-loop system.

1.1. Cylinder pressure measurement

Cylinder pressure has long been recognized as a primary indicator of combustion performance in automotive engines. In recent times, the sensor technology and cost have rapidly improved, and, with the advent of fiber-optic based sensors, are approaching economic viability for use in production vehicles. Pressure sensors do not require time for warm-up, as do conventional catalytic oxygen sensors. This benefit is crucial during the cold start period. Cylinder pressure sensing is a technology enabling much tighter control of air–fuel ratio under cold and lean conditions, as well as several other functions including knock control and injection and ignition system diagnosis.

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Cylinder pressure has been investigated over the last 20 years for use in closed-loop control schemes. Several approaches for best use of the information from cylinder pressure have been proposed [1–3]. Most statistical approaches that have been previously proposed use measurements over a large number of cycles, and therefore limit the bandwidth of a closed-loop control system. For example it has been stated by Brunt et al. [4] that up to 300 engine cycles are required to achieve acceptable repeatability and accuracy. Even at higher engine speeds, this requirement limits the sensor response (including processing) to 6 s.

The method proposed here compares pressure data from one cycle with the previous cycle, which dramatically improves the bandwidth. Even at the lowest engine speeds the time response of this method is a maximum of 0.2 s.

2. Method overview

2.1. Background—indicated mean effective pressure (IMEP)

The IMEP has long been used as an indicator of engine performance. It is defined as the amount of work done by the compressed gas scaled by the engine displacement volume:

$$\mathrm{IMEP} = \frac{W_\mathrm{c}}{V_\mathrm{d}} \tag{1}$$

where W_c is the work per cycle, calculated from pressure–volume measurements:

$$W_\mathrm{c} = \oint p \;\mathrm{d}V \tag{2}$$

and V_d is the engine displacement volume. The *gross* indicated mean effective pressure ($\mathrm{IMEP_g}$) involves the work done during the compression and expansion strokes of the cycle. It is calculated as the IMEP over the 180 before top-dead-center (BTDC) to 180 after top-dead-center (ATDC) crank angle interval. In our computations, $\mathrm{IMEP_g}$ is evaluated as a finite difference approximation of the integral:

$$\mathrm{IMEP_g} = \sum_{i=-180}^{180} p(i)\Delta V(i) \tag{3}$$

2.2. Cycle-to-cycle variations

The greatest difficulty with using feedback of IMEP or other values computed from the cylinder pressure trace for engine control is cycle-to-cycle variation of combustion. Fig. 1 shows an example of variation in cylinder pressure versus combustion chamber volume for a steady low-load operating condition on a warmed-up engine. Even under these normal, steady operating conditions, large cycle-to-cycle variations in cylinder pressure are present. Under lean or cold conditions, the mixture is weaker and/or more heterogeneous, and rates of combustion are slower and more sensitive to local conditions near the spark plug, resulting in much larger variations. Fig. 2 shows IMEP on a cycle-by-cycle basis for conditions similar to those in Fig. 1, and one can more clearly see the time progression of the calculated IMEP. Fig. 3 shows IMEP vs. time for a lean condition, and illustrates the increased cycle-to-cycle IMEP variation as air–fuel ratio increases.

To use IMEP values as a feedback signal in a closed-loop control system, the values would need to be in some way low-pass filtered or averaged. This requires

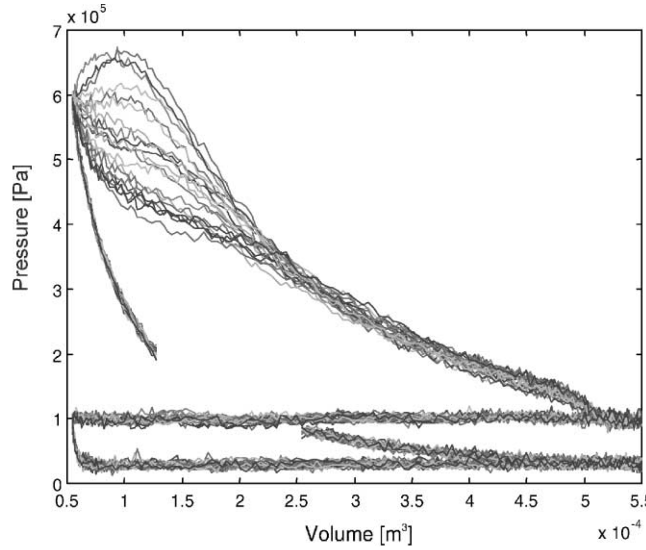

Fig. 1. Cycle to cycle variations of cylinder pressure traces for several light load cycles (Gap in data due to acquisition system limitations).

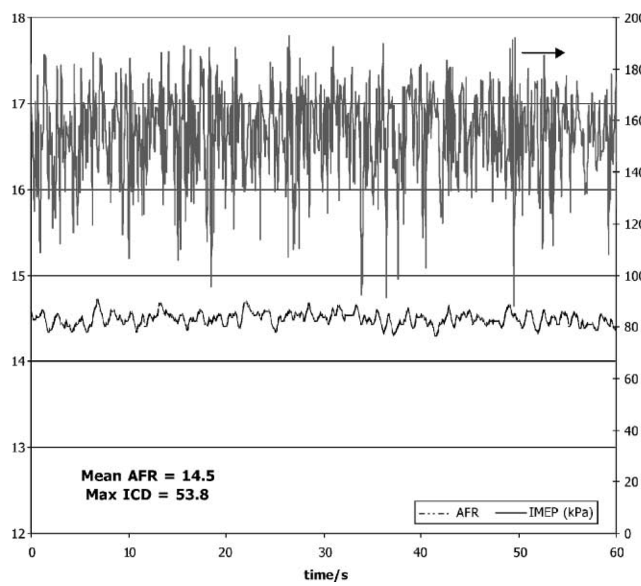

Fig. 2. Variation of $\mathrm{IMEP_g}$ at near stoichiometric conditions.

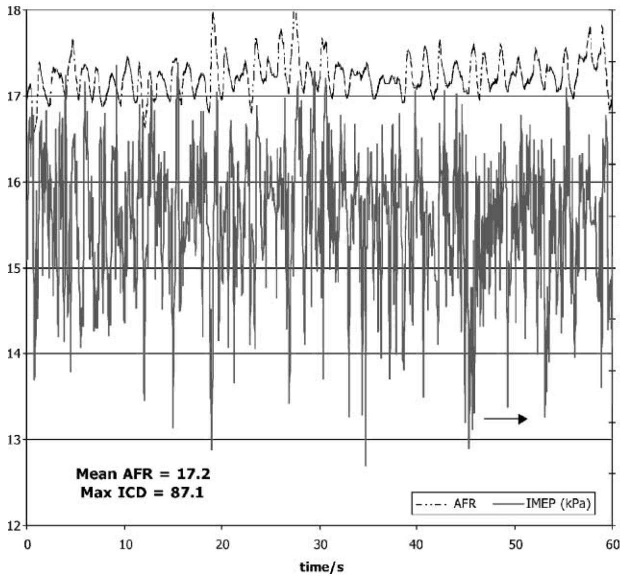

Fig. 3. Variation of $IMEP_g$ near lean limit.

a large number of cycles to get reasonable accuracy, and as the operating conditions change, the statistics must be reset. In this sense multi-cycle statistics and average values are not well suited for closed-loop control because of the bandwidth limitation they impose, and because of the problems associated with transients.

An interesting feature of the IMEP evolutions in Figs. 2–3 is the way the IMEP varies from cycle-to-cycle, i.e. intermittent large drops from one cycle to the next, and with increasing AFR these drops get more frequent and larger. We propose a simple method of detecting the onset of poor combustion by using this characteristic of the $IMEP_g$ history.

The method proposed here compares IMEP from one cycle to the next cycle can be used to maintain combustion under these lean conditions at some predefined level of stability based on the occurrence of large drops of IMEP, rather than on multi-cycle statistics or averages. The onset of poor combustion is detected with only one engine-cycle delay.

2.3. Closed-loop control using the IMEP drop detection

To respond to the drops in IMEP the basic idea is to immediately richen the mixture, preventing a perceptible roughness of combustion. As long as large drops in IMEP do not occur, the mixture is slowly leaned out, by increasing airflow, or decreasing fuel flow. This strategy is very similar to a knock-control strategy, where the knock sensor detects autoignition above a certain level of intensity and this signal indicates to the controller that the ignition timing should be retarded suddenly to prevent repeated knock.

In the first experiments, the air-fuel ratio is by manipulating the idle-air valve. The opening is gradually increased until the IMEP-drop the condition is met. At this point the idle-air valve opening is immediately reduced by a small amount, richening the air-fuel mixture. Afterwards the gradual increase of the airflow is resumed.

Then we then consider fuel flow as the control input. Here, the airflow is held steady while the amount of fuel injected is steadily decreased. Once the IMEP-drop condition is met, the amount of fuel injected is raised by a small amount, and then resumes its gradual decrease.

The first strategy has the advantage that under lean conditions the power level depends almost entirely on fuel flow, and not on airflow. Thus, airflow can control the air-fuel ratio without changing the idle speed, which would need to be corrected by changing the fuel flow. Another conceptual advantage of airflow as an actuator is that the complicated dynamics of fuel-puddling do not become involved, thus the airflow actuator should have a closer to linear effect when compared to fuel flow.

3. Apparatus

The engine used for this work is a Ford 3.0L V6 with electronic sequential port fuel injection. Cylinder pressure is measured using an inexpensive optical pressure transducer. The pressure sensor face is mounted flush with the combustion chamber near the spark plug in order to minimize changes in combustion chamber geometry.

Cylinder pressure is acquired and analyzed using a commercial data acquisition board with on-board TI digital signal processor (DSP). Data is collected on a crank-angle basis by clocking with a crankshaft-mounted incremental optical encoder. The DSP communicates with a Windows-based host computer over the ISA bus. The cylinder-pressure data are reduced to once-per-cycle measurements by the DSP and passed to the PC.

The host PC acquires other engine data and performs the closed-loop control of fuel injection, spark ignition, and airflow. The low-level pulse-sequencing to fuel injectors, spark modules and idle-air control valve are taken care of by hardware counters. The counters are contained on an ISA-bus plug-in board and programmed by a Windows application.

The Windows applications share data using dynamic data exchange (DDE), which is a protocol for sharing memory between Windows applications. The cylinder pressure application sends pressure based cycle parameters to the controller application, and the controller application sends fuel, spark and IAC commands to the counter programming application.

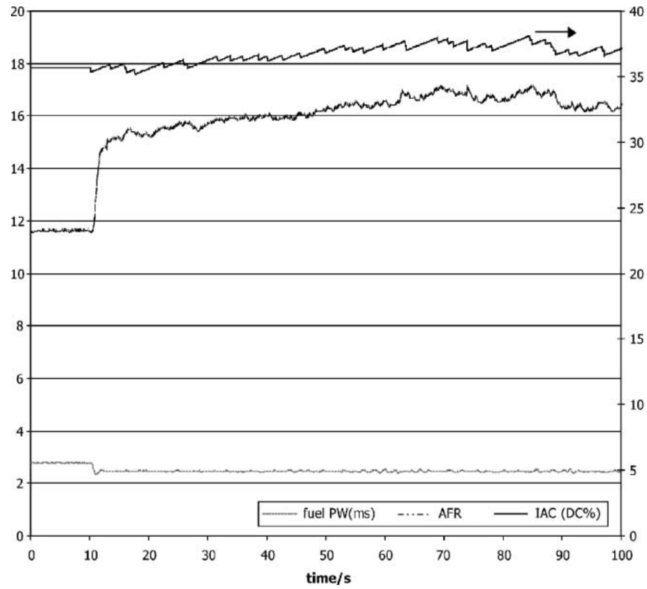

Fig. 4. Lean limit IMEP-drop detection control.

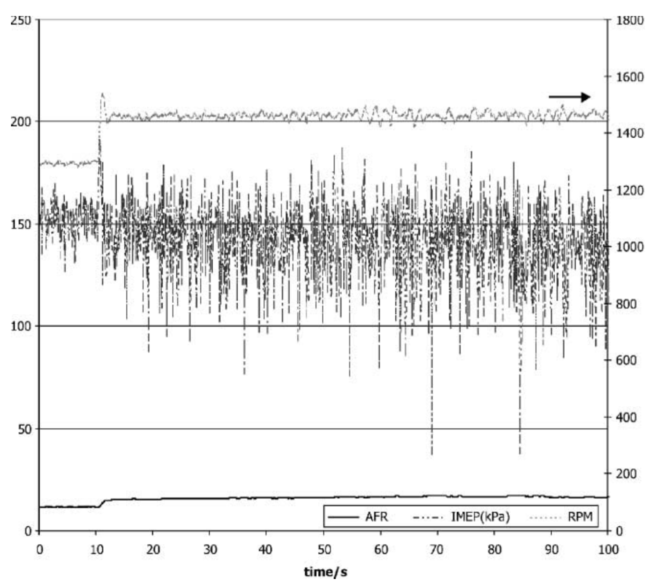

Fig. 5. Engine speed, IMEP, AFR during lean limit IMEP-drop detection control.

4. Experimental results

For the first set of experiments the IMEP-drop controller was validated under warmed-up conditions using a constant fuel flow rate and spark angle, and varying the idle-air control (IAC) valve opening. A base or feedforward airflow is calculated using a curve fit of steady state airflow values versus IAC position to find a nominal IAC position as a function of the commanded fuel flow. This is possible since the flow is always choked through the IAC, and thus the airflow depends only on the IAC valve open area, and nearly linearly so.

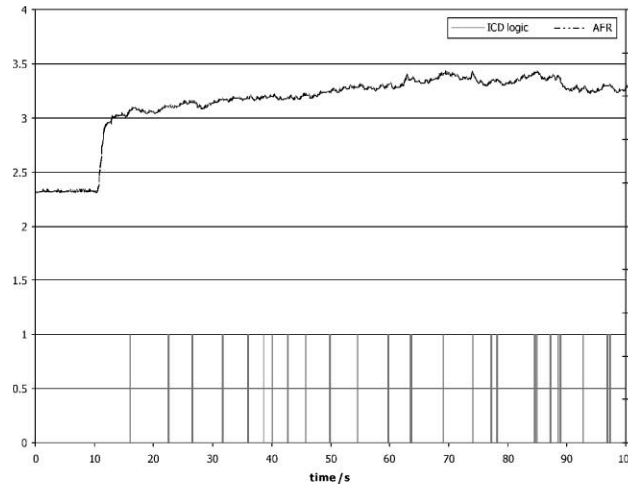

Fig. 6. Lean limit IMEP-drop detection logic signals and corresponding AFR.

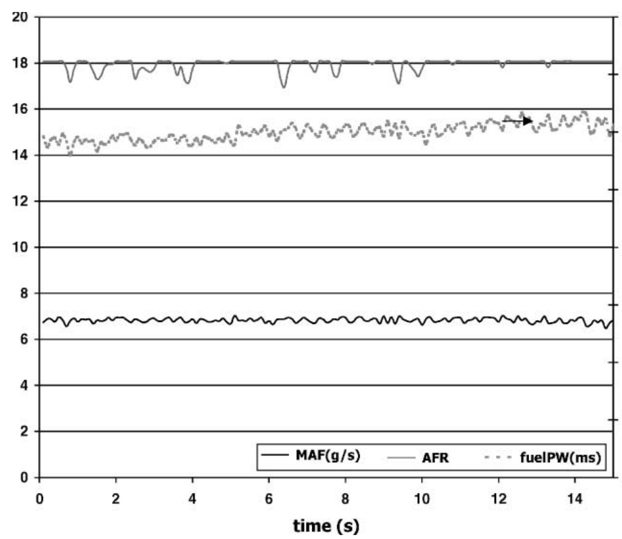

Fig. 7. Mass air flow, air fuel ratio, and fuel pulse width measurements during IMEP-drop detection lean limit control using fuel as control input.

Figs. 4–6 show the results of the closed-loop control experiment using air flow as the control input. It can be seen that the controller quickly approaches the lean limit as defined by the IMEP-drop condition. Once in the vicinity of the lean limit, the AFR remains at a value of approximately 16.5 and wanders only slightly in response to the very random fluctuations of the $IMEP_g$.

Fig. 7 shows the results when the injected fuel is used as the control input. In this test you do not see the turn-on of the system, but you can see steady operation at approx. 18 AFR. These experiments were done with constant airflow on a warm engine, so the fueling

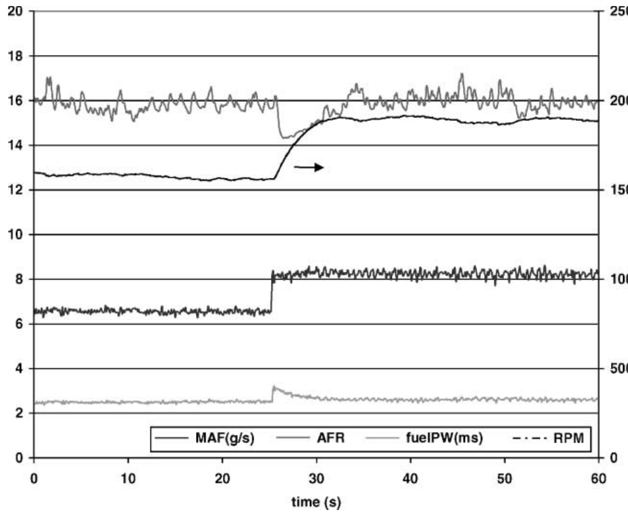

Fig. 8. Closed loop control using fuel as control input during a step increase in air flow.

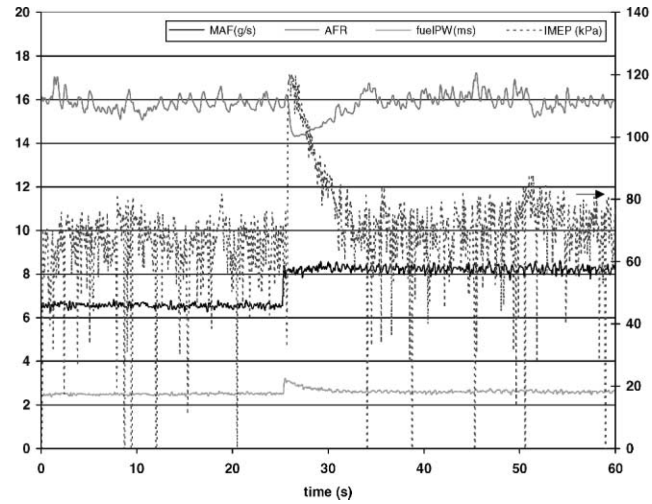

Fig. 9. IMEP, MAF, AFR, and fuel for closed loop control during a step increase in MAF.

dynamics are simpler than at cold temperatures, when complications such as fuel puddle formation are expected.

The well-behaved response of the closed-loop system to a step change in airflow is presented in Figs. 8 and 9.

5. Conclusions and future work

This work shows that IMEP-drop detection can be used for lean limit control of a spark ignition engine. Even with a simple control algorithm like the ones presented in this paper, smooth engine operation can be maintained near the lean limit.

We also show that the airflow is well suited as control input for lean limit control. This makes sense since under lean conditions the power level depends almost entirely on fuel flow, and not on airflow. Thus, AFR control is decoupled from power-level or idle-speed control.

Future work includes validation of suitability of the technique for operation under time-varying cold-start conditions, and inclusion of models in the control structure.

6. Uncited References

[5–12].

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