

Dynamic Engine Control for HCCI Combustion

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ABSTRACT

One of the factors preventing widespread use of Homogeneous Charge Compression Ignition or HCCI is the challenge of controlling the process under transient conditions. Current engine control technology does not have the ability to accurately control the individual cylinder states needed for consistent HCCI combustion. The material presented here is a new approach to engine control using a physics-based individual cylinder real time model to calculate the engine states and then controlling the engine with this state information. The model parameters and engine state information calculated within the engine controller can be used to calculate the required actuator positions so that the desired mass of air, fuel, and residual exhaust gas are achieved for each cylinder event. This approach offers a solution to the transient control problem that works with existing sensors and actuators.

The initial goal of this project was to develop a physics-based approach to controlling engines with a cam-less or fully flexible valvetrain system. The model and control strategies that were developed can be applied to many internal combustion engine applications. The HCCI application in particular benefits the most from this technology because of the improved control of cylinder air mass and mixture composition. The real time one-dimensional flow model and the individual cylinder model developed during this project are explained. A single cylinder spark ignition research engine with cam-phasing and interchangeable camshafts was used for evaluating model parameter estimation and engine control performance. Test data is shown comparing estimated and measured pressures in the intake manifold and cylinder. The applicability of this control strategy to HCCI is discussed.

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INTRODUCTION

The potential use of Homogeneous Charge Compression Ignition or HCCI in internal combustion engines has garnered a lot of interest by researchers and engineers because of the extremely low post-combustion levels of oxides of Nitrogen or NO_x that result from this approach. In HCCI very high levels of diluents or exhaust gas recirculation (EGR) are present in the cylinder, and distributed combustion occurs by means of compression ignition. The diluent lowers the concentration of O_2 thereby reducing the rate of NO_x formation, and keeps temperatures of the post-combustion gases low. Since the production of NO_x in these gases is principally a function of time and temperature, emission levels of NO_x are subsequently significantly lowered.

While these attributes are quite attractive, thus encouraging a lot of research and development in recent years, this approach also produces several difficulties in both

starting and controlling HCCI combustion in an engine, because the start of combustion is not directly influenced by the timing of the fuel injection (such as in a diesel or compression or CI engine) or by a spark event (such as in a spark ignition or SI engine). There have been several different approaches to addressing these problems, but with limited success or some unrepeatability results, significant problems remain. This paper presents a new approach to controlling HCCI combustion, and directly addresses many of the problems in typical engine control today that exacerbate the difficulties of successfully controlling HCCI start of combustion.

ENGINE CONTROL STATE-OF-THE-ART

If we examine the typical approach to engine control today, this will help us understand why continuing along this

approach not only does not lead to careful or accurate control of HCCI combustion, but also compounds the problems. In a modern day SI engine the total air going into the engine is usually measured with a mass airflow or MAF sensor. This is typically a hot wire or hot film anemometer which estimates the mass flow rate through the device. An alternate means of estimating the airflow into the engine is by means of what is referred to as the "speed-density" approach. This approach uses the ideal gas law along with known engine parameters, measurements of pressure and temperature in the engine intake manifold, an average engine speed measurement, and a volumetric efficiency table, to estimate the total gas flow out of the intake manifold. With an estimate of either the average air or gas being used by the engine, a base fueling is calculated, and individual fuel injection timing and duration are controlled for each cylinder.

Once the exhaust catalyst has "lit off" or reached an operational temperature, the engine typically goes into a closed-loop control mode. An oxygen sensor senses the presence of oxygen in the engine exhaust stream, and a lagged electrical signal is fed back from this sensor to the engine control unit (ECU), which then adjusts the injector pulse duration based upon the assumption that the oxygen sensor signal is indicating either a lean or rich condition.

DOES THIS APPROACH WORK FOR HCCI?

Let's now examine whether continuing to apply this approach to engine control would be useful when trying to transition into an HCCI mode of operation, or in controlling HCCI combustion in this mode. It is well known that the start of combustion in HCCI is highly dependent upon the state of charge in the cylinder during compression, and small variations in this state can significantly change the point at which combustion begins or if it begins at all. If we look back at how a typical SI engine is controlled we see that both the fueling as well as the spark timing are based on engine-averaged variables. That is, only the average airflow into the engine or out of the intake manifold is either measured or estimated, and not the individual airflow into each cylinder. Differences between cylinders can and do exist, which leads to errors in forward estimation. This is especially true with external EGR, which is typically added to the intake manifold with the assumption of complete mixing with the intake air. Again, the level of EGR in each cylinder is not directly estimated, but perfect mixing and perfect distribution is typically assumed in the control of the engine and its emissions.

In the case where a speed-density calculation is made to estimate airflow, a volumetric efficiency table is used in this calculation, and this volumetric efficiency table is only based on steady-state operating states and contains no transient information when cylinder states are changing. However, if we look at typical engine operation we see that through much of the operating cycle the engine is going through transients.

Another issue with using a speed-density calculation for estimating airflow is that this estimate is always looking backward, or estimating the airflow for the last intake event. Therefore, fueling is always misaligned or one cycle behind or delayed from where it should optimally be. That is the engine senses what the airflow is on a particular cycle, but does not use that information until the next cycle. This is an issue during transients, and ad hoc modifications to fueling based on throttle position are sometimes added to try to minimize this problem.

In the case where the engine goes into closed-loop control based on an oxygen sensor signal, it is clear that not only is this signal lagged because of the dynamics of the sensor, but also the measurement is made after the engine cycle is completed and exhaust occurs. Therefore, fueling based upon this signal is not only delayed by the engine cycle, but also lagged by the sensor. Therefore, there is a significant misalignment of fuel and air because of both the delay of the engine cycle as well as the lag of the sensor. This misalignment can cause problems during transients. Another issue with this feedback approach is that the oxygen sensor doesn't measure whether the air/fuel ratio is rich or lean, but only measures the presence of oxygen. During misfire this can cause significant problems. For example, if the average cylinder air/fuel ratio is rich and there is a misfire, the oxygen sensor senses oxygen in the exhaust and feeds back a signal indicating lean operation (i.e., oxygen present in the exhaust). The typical fueling calculation would lengthen the fuel pulse width and move the air/fuel ratio to a richer region and away from the desired level. Also, remember that the oxygen sensor is sensing oxygen from several cylinders' exhaust mixed together and not from an individual cylinder. This averaged delayed, averaged, and lagged signal can lead to degraded control of the combustion especially during transients because the closed-loop fueling is based on this sensor signal.

It is fairly clear that current engine control is either based on engine-averaged estimates or steady-state data or signals that are lagged or delayed, and these cause measureable misalignment in time between airflow and fuel flow into each cylinder. While this has produced acceptable results for conventional combustion, this approach falls short for controlling HCCI combustion that is very sensitive to the individual cylinder state of charge.

WHAT MIGHT BE AN OPTIMAL APPROACH?

If we step back and brainstorm what would be a desired situation for control of HCCI combustion knowing its sensitivities, one situation would be to know what each individual cylinders' state of charge would be ahead of time, and then to be able to add fuel or EGR or possibly control valve actuation for that particular cycle in order to best control the start of combustion for HCCI.

DISCUSSION

This project started with the goal of finding a better way to control engines with cam-less or fully flexible valvetrain systems. Traditional engine control strategies using speed-density models become increasingly more difficult to calibrate as more valve timing and valve lift actuation strategies are implemented. In addition, the mean value engine models that are commonly used for engine control today are not able to accurately predict the state of each engine cylinder under transient conditions. The new approach to engine control presented here offers better parameter estimation and control of the individual cylinder states. A single cylinder spark ignition research engine with cam-phasing and interchangeable camshafts was used for developing and testing this new strategy. The following discussion describes the models and controls that were developed. The “Applicability to HCCI Control” section describes how these strategies can benefit the HCCI application.

To improve engine control with any combination of valve timing and valve lift the approach taken on this project was to use physics-based models instead of steady state maps to characterize the flows through the valves. To determine valve flow with this method the fluid states must be known on each side of the valve so that the flow can be calculated. Measuring these states or the flow through the valve was considered impractical for a production application because of cost and reliability concerns for sensors in these locations. Also, for a port fuel injected engine the measured states for the intake valve flow calculation would occur after the fuel was injected so it would be difficult to control the air to fuel ratio. It is generally more accurate to control the fuel injection to match the airflow rather than controlling the airflow to match the fuelling. The fuel injection pulse width can be adjusted accurately for each cylinder event where the valve opening cannot (unless it is a cam-less engine with independent valve actuators). Measuring or estimating the intake valve flow after the fuel has already been injected does not allow any fuelling adjustments to be made for that cylinder event.

By using a model of the intake system, cylinder, and exhaust system, it is possible to predict many engine states before they occur in the actual process. The model can run ahead of the real engine to predict these states, and if certain states are desired the model can be inverted to determine the actuator commands that will result in the desired states occurring on the real engine (as long as they are physically possible). The engine model developed for this project was able to predict the mass of air in the cylinder over a wide range of valve timing and valve lift. This allowed the fuel injection and spark advance to be set correctly for each cycle of the cylinder. The model was set to run ahead of the real engine so that the correct fuel injection quantity could be delivered in time to make it into the cylinder with the air on the intake stroke. A wall-wetting model was used to adjust the fuel injection mass to compensate for fuel impacting the

valve and port walls as well as evaporation of fuel from the fuel film in the ports [1]. Such a model would not be needed with direct fuel injection.

The engine model was set to run at a fixed time of 100 ms ahead of the real engine based on the minimum time required to deliver the correct amount of fuel before the intake valve closes at low engine speed. At high engine speeds several engine cycles may occur within 100 ms so the mass of air per cylinder estimate had to be carefully coordinated so that the correct estimate was used for the current engine cycle. Although a fixed time 100 ms prediction was used for this first implementation, an alternative would be to predict the engine states ahead by a certain crank angle (one engine revolution for example). With a fixed crank angle prediction, the simulated engine time would change as the engine speed changes meaning the simulation time interval during each controller time step would be adjusted to achieve the desired time in the future that corresponds to the desired crank angle. This alternative approach would be more difficult to implement but could provide slightly better estimates because it would not have to predict states as far into the future.

By modeling each cylinder event in this way, transient events were treated exactly the same as steady state events. In fact, each cylinder event really is a transient event because the flow through the valve is not steady. This approach provides better parameter estimation under transient conditions than steady state maps based on mean value engine models using delayed and filtered sensor readings as inputs.

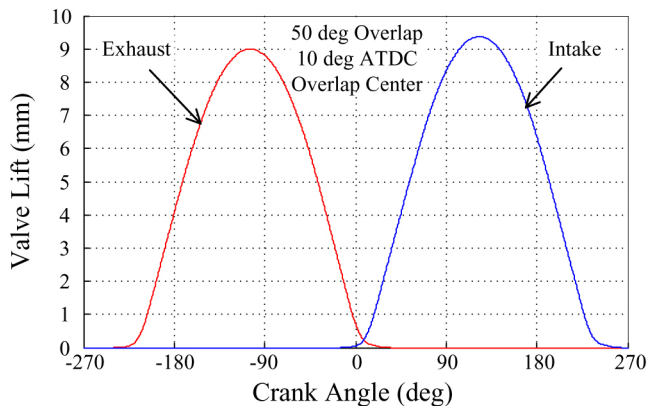
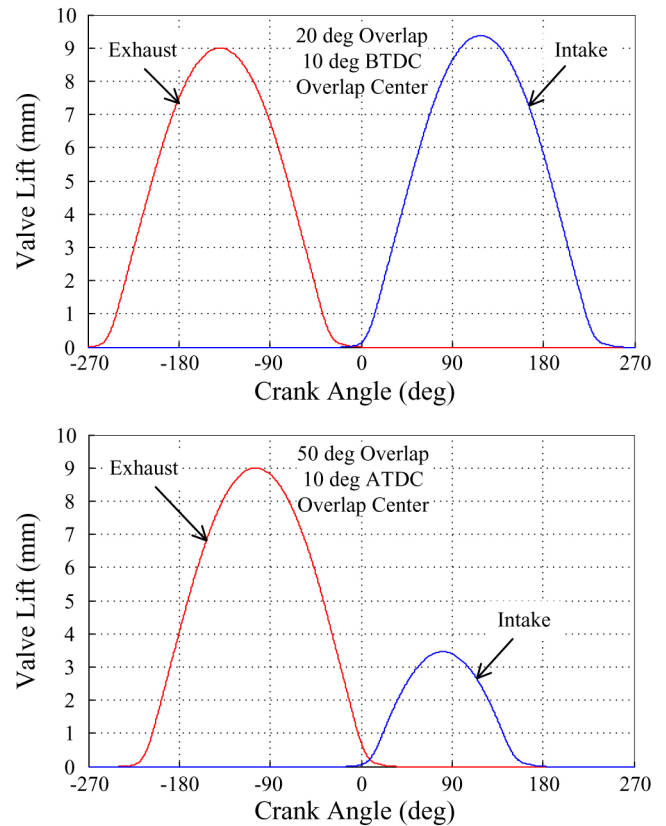
The engine model developed for this project was also used to control engine torque and the in cylinder exhaust gas residual mass fraction. With a few minor changes the model could be expanded to include features such as an external EGR loop, turbocharger, and additional engine cylinders. In an HCCI application the model and an inverted form of the model could be used to determine the actuator positions that are required for each cylinder combustion event far enough in the future so that the actuators have the desired effect on the process.

The engine model for the project was created in C-code and the controls were implemented in Simulink. Real Time Workshop was used to automatically generate software code for a DS1005 dSPACE rapid prototyping controller. The controls were tested on a single cylinder Ricardo research engine. [Table 1](#) provides a summary of the engine specifications.

Table 1. Engine Specifications

Engine Type	Single Cylinder, 4 Valve DOHC, Port Fuel Injection, Spark Ignition, Electronic Throttle Control
Displacement	0.55 L (single cylinder)
Bore	86.0 mm
Stroke	94.6 mm
Connecting Rod Length	157.1 mm
Compression Ratio	9:1
Intake Cam Lift	9.4 mm or 3.5 mm
Exhaust Cam Lift	9.0 mm
Intake Valve Opening Duration	280 crank angle degrees (9.4 mm Camshaft) 198 crank angle degrees (3.5 mm Camshaft)
Exhaust Valve Opening Duration	275 crank angle degrees
Intake Valve Diameter	33.4 mm (2 intake valves per cylinder)
Exhaust Valve Diameter	27.3 mm (2 exhaust valves per cylinder)
Fuel	93 Octane Number (R+M)/2 Gasoline

The engine used for this project utilized dual independent camshaft phasors. Intake camshafts with two different levels of valve lift were used to evaluate the model and controls. The same engine model and calibration were used for all combinations of valve timing and valve lift presented here. Figure 1 shows three of the valve timing and valve lift combinations that were evaluated. Test data for these valve lift profiles are presented in Figures 7, 8, 9, 10 and Figures 15, 16, 17.

**Figure 1. Valve lift profiles (Continued)****Figure 1. Valve lift profiles**

A custom hydrostatic dynamometer was designed specifically for transient testing with this single cylinder engine, Figure 2. The dynamometer was capable of cancelling the instantaneous torque produced by the engine so that the speed could be accurately controlled without the use of a flywheel. The combination of high torque capability, fast response, and no flywheel made the dynamometer ideal for transient speed testing. The controls for the dynamometer were integrated with the engine model. The cylinder pressure estimate from the engine model was used to calculate the speed trajectory that would occur in a multi-cylinder engine. The single cylinder dynamometer was controlled to cancel the instantaneous torque produced by the engine at each crank angle throughout the engine cycle and then apply feed forward and feedback control to achieve the desired multi-cylinder speed trajectory [2],[3].

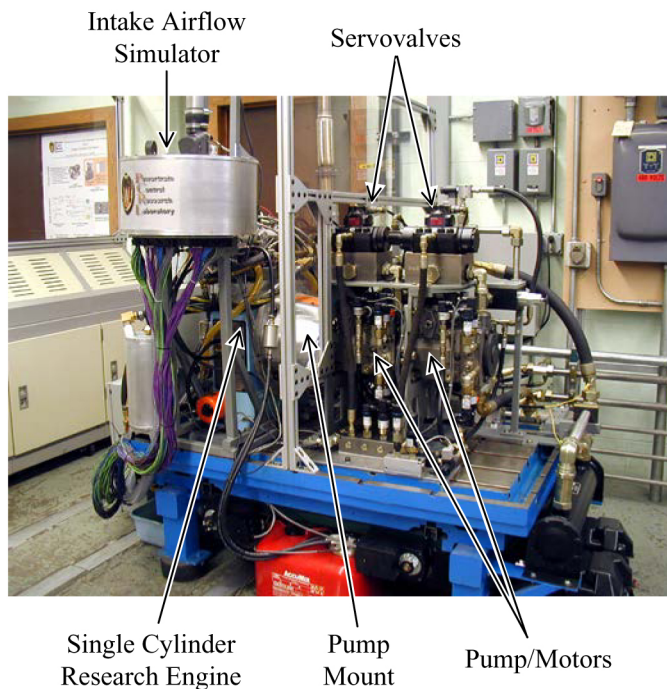


Figure 2. Single cylinder engine and hydrostatic dynamometer

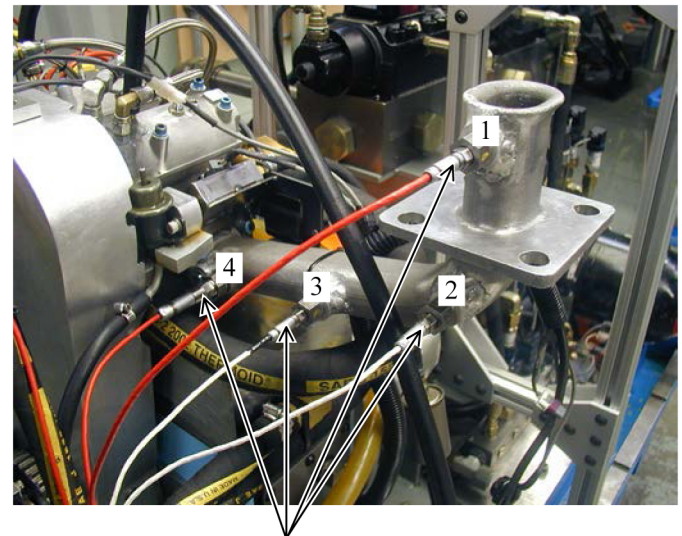
The dynamometer was just one part of a single cylinder transient test system that was being developed at the University of Wisconsin - Madison at the time of this research. Other parts being developed, but not complete in time for testing on this project, were the intake airflow simulator and the transient heat transfer system. The intake airflow simulator was designed to improve the intake manifold dynamics on the single cylinder engine by creating airflow from the intake manifold to virtual cylinders using a vacuum pump and solenoid valves [4]. The transient heat transfer system controls the engine coolant temperature by regulating flows from high temperature and low temperature reservoirs to simulate the cold start and warm-up operation of a multi-cylinder engine [5].

The complete single cylinder transient test system makes it possible to accurately reproduce the cold start, warm-up, and transient operation of a multi-cylinder engine on a standard emission test drive cycle using a single cylinder engine. This capability greatly expands the usefulness of the single cylinder engine for research and could significantly reduce the time and cost for engine development.

The following section provides an overview of the spark ignition engine model that was developed and explains how it was integrated with the engine control system. Test results show how the estimated model parameters compare with the measured states on the engine. The concepts developed using the spark ignition engine are applicable to a wide variety of internal combustion engines.

WAVE DYNAMICS

The first step in developing the model for the engine was to study the wave dynamics for the intake runner (i.e. the passage from the intake plenum to the intake valve). Pressure transducers were installed along the length of the intake runner as shown in Figure 3. A model of the intake runner was then developed that used measured intake plenum pressure and measure cylinder pressure as the boundary conditions. As other parts of the model were develop, the measured intake plenum pressure and measured cylinder pressure were replaced with modeled parameters.



Pressure Transducers

Figure 3. Intake runner pressure transducers

The single cylinder engine used for this analysis had a normal size intake plenum but it was only supplying one cylinder. The resulting airflow through the throttle was less than normal because it was supplying only one cylinder. Since airflow was only drawn from the intake plenum during the intake stroke the pressure in the plenum had a saw tooth profile as shown in Figure 4. The amplitude of the saw tooth profile would be less and the frequency would be higher on a multi-cylinder engine. The intake airflow simulator mentioned earlier and shown in Figure 2 was developed to simulate airflows from the plenum going to other cylinders of the engine. The airflow simulator was being developed at the same time as the engine model so the results in this paper are shown with the airflow simulator turned off.