Control-Oriented Modeling for HCCI Combustion and Multi-Cylinder HCCI Experimental Activities

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**Motivation for the Control-Oriented Approach**

- **HCCI with Diesel fuel has been experimentally demonstrated by many groups to be a worthwhile combustion option.**
- Various low EGR, emissions
- Reasonable efficiency
- One of the major challenges in the implementation of HCCI to practical engine combustion is the need for control over combustion timing (i.e., spark timing or injection timing)
- Minimizing control over combustion timing and burn rate is critical for achieving high efficiency operation and reasonable engine loads with acceptable cylinder pressure levels
- Combustion timing and burn rate are defined by the time-temperature history of the air-fuel-mixture before the actual mixture of the charge as the composition of the charge.
- With the loss of direct control over combustion, the engine control concept is found to be on actuators that on act on parameters that influence combustion indirectly: external EGR, trapped residual, charge temperature, boost pressure, and valve timing
- These indirect factors have many interrelations and overlap in their ability to control HCCI combustion, therefore achieving the desired outcomes can be achieved by many different paths
- Just as Control-Oriented Modeling is increasingly vital for advanced gasoline engine with similarly complex actuator set, it will have similar application potential to HCCI combustion

The work presented here is the early result of developing a control-oriented approach to HCCI combustion control.

**Goals of Research and the Approach**

- The goal of the research is to develop a simple engine model that is capable of capturing the behavior of the engine:
  - **Simple** Model: The model must be capable of capturing the main flame
  - **Relevant** Behavior: The model must accurately capture the dynamic, mean-value behavior of the intake and exhaust systems, the combustion chamber, and the burn rate distribution
- The approach taken to achieve the goals builds on the successes of two-decades of similar combustion, the sensitivity of the combustion to various factors, and explore control concepts

**Experimental Setup**

- Experimental facilities for the project are housed in the OSU Center for Automotive Research (see Figure 1.1)
- Engine was an on-line EGR engine with the following minor modifications
  - The intake and EGR cooler of the engine were maintained
  - The EGR valve was replaced by a higher precision EGR control system
  - The EGR system was controlled by an electronic control unit
- The engine maintained a stoichiometric ratio of 15:1 to ensure a stoichiometric combustion
- Fuel is injected into the intake manifold at a molar stoichiometry of 1.8:1
- The intake and exhaust manifolds were equipped with multiple fast-responding exhaust gas and intake air pressure sensors

**The Need for Control: Experimental Evidence**

- Figure 1 shows experimental results for increasing EGR at a constant fuel rate
- Increasing the residual gas has the effect of delaying combustion
- However, increasing residual gas tends to increase the charge temperature, which can also delay the onset of combustion

**Figure 6: Sensitivity of Fueling on Cylinder Pressure and Combustion**

- Figure 6 shows the high dependence of combustion on fueling
- Increased fuel rates lead to advanced combustion
- At high fuel rates, the addition of EGR is not enough to sustain combustion so the indicated efficiency is dramatically important

**Control-Oriented Combustion Model**

- CFD and chemical kinetics routines are too complex for a real-time control application
- The modeling structure used shown in Figure 10, has the use of Wiebe functions which are commonly used for gasoline combustion. This Wiebe function is a general expression for the combustion of a Diesel fuel
- The second Wiebe function captures the main flame chemistry
- The third Wiebe function captures the long duration of the slow heat release
- An "auto-ignition" Wiebe is used to accurately predict the start of the cool flame and temperature threshold was found to accurately model the start of the main flame
- The values in the parameters are burnable by trials, such as fuel amount, air mass, intake mass, charge temperature, etc.
- Figure 15 shows the characteristic Wiebe functions, which are each modeled by a single Wiebe function
- This simple model has proven capable of modeling HCCI combustion over a range of operating conditions

**Cylinder-to-Cylinder Variation**

- By using a multi-cylinder engine, it forces the experiments to be constrained to the operable range of a practical engine
- For instance, high boost pressures are difficult to achieve with HCCI because of high EGR rates and low load operation
- The case of a multi-cylinder engine also allows the testing of multiple cylinder effects
- Nonuniform distribution of air to individual cylinders
- Nonuniform distribution of EGR to individual cylinders
- Varying levels of heat transfer to the individual cylinders
- Figure 8 shows the cylinder-to-cylinder variation in IMEP for increases in fueling
- EGR is approximately 1 bar of EGR differences between adjacent cylinders
- Figure 9 shows a variation that the deviation from the highest to lowest efficient cylinder of nearly 10%
- Even with a completely homogeneous charge introduced into the intake manifold, cylinder-to-cylinder variation is expected due to imbalances in the mass of charge induced into each cylinder as well as thermal differences between cylinders

**Putting the Models Together**

- With the current experimental setup (manifold injection), individual cylinder fuel trimming is not possible. In the future, part injector will be used to allow a means of allowing cylinder-by-cylinder control

**Conclusions and Future Work**

- The multi-cylinder research has demonstrated that an essentially unmodified diesel engine can be successfully run in HCCI using external mixture preparation. This method of combustion has demonstrated similar BSFC and dramatically improved NOx emissions at the light loads possible with the current experimental engine. Furthermore, relatively simple models can be used to provide useful models of HCCI engine
- Experience and Modeling of a Variable Cam Engine: Experiments to show how the use of a variable cam engine can be used to effectively control cylinder-to-cylinder variation and extend the load range of the HCCI combustion, it is necessary to allow for variable cam timing, since cam profiles can be quite different. One method of delaying the onset and slowing the rate of combustion is through variable valve timing. This can be achieved by actuation of variable cam hardware
- EGR System model (with cooler)
- Intake manifold model (with nonmixture injection)

**Experimental Setup**

- This validation is for the entire model framework (control-oriented combustion model) and shows good agreement
- The model is to be accurately predict the conditions at intake valve closing, which then feed the initial conditions for the combustion model.

**Putting the Models Together**

- The Mean-Value Air-Loop model and the combustion model is integrated into a Matlab-Simulink simulator
- The gasoil model simulates the intake manifold, exhaust manifold, turbocharger, intercooler, EGR valve, and EGR cooler; this results in the determination of the change compartment pressure at intake valve closing
- From this point, the combustion model calculates the heat loss of the intake in the cylinder which leads to a pressure which is used to calculate the torque production of the engine
- The upper plot in Figure 17 shows a simulated step in EGR valve position, from fully closed to fully open
- The lower plot shows an initial rapid change in IMEP due to new air/fuel ratio, and exhaust gas flow rate, which is followed by a much slower change in the IMEP
- Figure 18 shows the evolution of cylinder pressure near the second transient transition
- The upper plot shows the variation in heat release
- The lower plot effectively shows how the heat release is affected by the step signal to the EGR valve
- For a SIMPLER approach to this open loop step input, the IMEP has an initial overshoot before returning to the new steady state
- This simple exercise shows the degree that combustion can change over even a small EGR maneuver
- A control software is to control the simulation engine and multi-cylinder combustion

**A Mean-Value HCCI Air-Loop Model**

- Figure 11 shows a schematic of the components of the mean value model deli very
- Submodels include:
  - Mean-Value Combustion model
  - EGR System model (with cooler)
  - Intake manifold model (with nonmixture injection)

**Conclusions and Future Work**

- The current work focuses on what is essentially a retrofit of the current engine
- With the presence of many indirect and overlapping methods of controlling HCCI combustion, some method of arbitration between what actuators are used is necessary. One method is to use a combustion model such as the one presented to determine the conditions at intake valve closing and avoid the initial combustion in order to avoid premature combustion
- The current work focuses on what is essentially a retrofit of the current engine

**Controlled Experimental Data for Under- and Overloads and Pressure**

- The model must be capable of running in real-time or faster
- A “Simple” Model: The model must be capable of running in real-time or faster
- The approach taken to achieve the goals builds on the successes of two-decades of similar combustion, the sensitivity of the combustion to various factors, and explore control concepts

**Figure 8: Cylinder-to-Cylinder IMEP**

- Developing a control that can manage the HCCI system during transient is a key challenge for implementing any HCCI system.