Cycle-to-cycle Control of HCCI Engines With Variable Valve Actuation

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Lab Overview

- Currently ~ 16 Students (10 PhD, 4 MS, 2 BS)
  - Engine work – 2 PhD, 1 BS, adding 1 MS in Fall
- Other research in vehicle dynamics and control
  - Lanekeeping
  - Diagnosis and handling modification with by-wire systems
  - State estimation with GPS / Steer-by-wire / EPS
- Research test fleet
  - Mercedes E320
  - Ford Windstar
  - Chevrolet Corvette (Steer-by-wire)
  - Custom designed steer-by-wire vehicle
The HCCI Team

- Graduate student researchers:
  - Gregory M. Shaver
  - Matthew R. Roelle

- Our thermodynamic colleagues:
  - Prof. Christopher F. Edwards
  - Patrick A. Caton
  - Han Ho Song

- Laboratory support:
  - Scott Sutton
  - Nalu Kaahaaina

- Our partners and sponsors at Bosch
Outline

- Challenges/Opportunities for control in HCCI
  - Motivation for modeling and control

- Modeling of residual affected HCCI
  - Basic model and ignition criteria
  - Transient behavior and implications for control

- Control model and controller design
  - IVO/EVC in tandem with peak pressure feedback

- Combined load and phasing control
  - Two approaches and current work
Residual Affected HCCI

- **HCCI** – Homogenous Charge Compression Ignition
  - Combustion by auto-ignition alone

- **Potential benefits**
  - Higher efficiency
  - Lower emissions
  - Combine best aspects of SI and CI

- **Must increase initial energy in cylinder**
  - Preheat or pre-compress the intake stream
  - Change compression ratio
  - Reinduct or trap exhaust gas with valves
Residual Affected HCCI

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Variable Valve Actuation

- **Stanford VVA system**
  - Built in 1980’s
  - Control system rebuilt 1999

- **Electrohydraulic system**
  - Fully variable lift and timing
  - Operates at 1800rpm

- **Closed-loop control**
  - LVDT based feedback
Starting Point – Change Valve Timing

- Consider only valve timing for now

- Initial control knobs:
  - IVO
  - EVC
  - Sufficient for simple controller design

- Add another later:
  - IVC
  - Changes effective compression ratio
Challenges/Opportunities in HCCI with VVA

- Variable valve actuation
  - Valves are (only) input

- No direct initiator of combustion
  - Must vary valves to ensure correct phasing
  - Phasing is key control challenge (?)

- Cycle-to-cycle coupling through exhaust gas
  - History of previous cycle(s) is important
  - With control an opportunity to reduce cyclic dispersion
Desired trajectory gives high efficiency, low emissions

- Premixed propane at fixed intake equivalence ratio
- HC likely due to mixing issues
Phasing on Desired Trajectory

- Angle of peak very constant on ideal emissions trajectory
  - Desired trajectory is generally a tandem shift of IVO/EVC

![Graph showing IVO (°ATC IVO) vs EVC (°ATC IVO)]

- Increasing load
Our Control Engineering Approach

“Everything should be made as simple as possible, but not simpler.”
-Albert Einstein

“All models are wrong. Some are useful.”
-George E. P. Box

Objective: Simple physical models and controllers
- Map inputs to system dynamics
- Understand approximately how to adjust input to get desired behavior
- Use feedback to correct for model imperfection

Sophistication in proving stability, boundedness, etc.
Open-system first law analysis of cylinder & exhaust manifold
Multi-cycle HCCI Simulation Model
(Shaver et al., 1st IFAC Symposium on Advances in Automotive Control, 2004, Pages 244-249)

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- Steady state 1D compressible flow relations for valves
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- Heat transfer
  - In-cylinder (Woschni)
  - Exhaust manifold
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- Open-system first law analysis of cylinder & exhaust manifold
- Steady state 1D compressible flow relations for valves
- Heat transfer
  - In-cylinder (Woschni)
  - Exhaust manifold
- Combustion model
  - Extent of reaction from Wiebe function after initiation
  - What do we use as a trigger for HCCI combustion?
Assume HCCI occurs at a threshold temperature
  ● A fit at one temperature…
Assume HCCI occurs at a threshold temperature
- Fit at one temperature… doesn’t hold at others!
What Happened?

- Simulation model: earlier phasing for lower loads
  - Lower load has higher residual fraction
  - Higher residual fraction means higher temperature
  - Higher temperature leads to early phasing

- Experiments show more constant phasing

- Is some physical effect missing?
  - Yes! Concentration of reactants
  - More exhaust gas reinduction leads to dilute mixture
Integrated Arrhenius Rate Equation

- Simple model for phasing and extent of reaction
  - Initiation: Integrated Arrhenius rate
    
    \[
    \text{threshold} = \int_{IVC}^{\theta_{comb}} A \exp \left( \frac{E_a}{RT} \right) [C_3H_8]^a [O_2]^b \, d\theta
    \]
  - Constant threshold works well
  - Values for \( a \), \( b \) and \( E_a \) from published experiments

- Different from knock integral:
  - In knock integral \( a = b = 0 \)
  - Concentrations are not included
Integrated Arrhenius Rate

- Set threshold at one operating point…
Set threshold at one operating point…
…and phasing at all points is captured
Knock Integral

- Shows similar behavior as temperature threshold
  - Concentrations are very important
Multi-cycle HCCI Simulation

Valve Profiles

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>IVO</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td>EVC</td>
<td>180</td>
<td>185</td>
</tr>
</tbody>
</table>

- Transient effects
  - Predicted by model
  - Capture phasing
  - Physical motivation

- Model validated
  - On ideal trajectory
  - Off of trajectory
Results from Modeling

- Residual affected HCCI is self-stabilizing
  - Phase remains fairly constant on ideal trajectory
  - Behavior predicted by integrated Arrhenius rate
- Can map tandem valve shift to ratio $\alpha = \frac{N_p}{N_r}$
A Simple Control Strategy
(Shaver and Gerdes, Proceeding of the 2003 ASME IMECE IMECE2003-41966)

Use variable valve actuation to:
- Vary molar ratio, $\alpha$, to get desired work output
- Use peak pressure as a proxy for work output
- Use self-stabilizing nature to maintain phase

Still need a simpler model:
- Input: $\alpha = N_p/N_r$ (composition)
- Output: peak pressure (measurable quantity)

Step through process to determine model
- How well will this indirect phasing control work?
Assumptions:

- No significant heat transfer
- Constant atmospheric pressure
- Full mixing

1st law of thermodynamics gives:

\[
T_1(k) = \frac{C_1 T_{inlet} + C_2 \alpha(k)T_{inlet,prod}}{C_1 T_{inlet} + C_2 \alpha(k)}
\]

\[
C_1 = \phi \bar{c}_{p,C_3H_8} + 5\bar{c}_{p,O_2} + 18.8\bar{c}_{p,N_2}
\]

\[
C_2 = 3\phi \bar{c}_{p,CO_2} + 4\bar{c}_{p,H_2O} + 18.8\bar{c}_{p,N_2} + 5(1-\phi)\bar{c}_{p,O_2}
\]
Assumptions:

- Compression is isentropic

\[ T_2(k) = \left( \frac{V_1}{V_{23}} \right)^{\gamma^{-1}} T_1(k) \]

\[ P_2(k) = \left( \frac{V_1}{V_{23}} \right)^{\gamma} P_{atm} \]
Assumptions:

- HCCI is fast: constant volume combustion to major products
- Heat transfer is $\%$ of available reactant chemical energy, $\varepsilon$

1$^{\text{st}}$ law of thermodynamics and ideal gas law give:

$$T_3(k) = \frac{C_4 + \left( C_1 + C_2\alpha(k) \right) T_2(k)}{C_2 \left(1 + \alpha(k) \right)}$$

$$C_4 = (1 - \varepsilon)\left( \phi LHV_{C_3H_8} + (C_2 - C_1)T_{ref} \right)$$

$$P_3(k) = \left( \frac{V_1}{V_{23}} \right)^\gamma \frac{C_1 + C_2\alpha(k)}{C_2 \left(1 + \alpha(k) \right) T_3(k) - C_4} P_{atm} T_3(k)$$
Assumption:

- Expansion/exhaust are isentropic

\[
T_4(k) = \left( \frac{V_{23}}{V_4} \right)^{-1} T_3(k)
\]

\[
P_4(k) = \left( \frac{V_{23}}{V_4} \right)^\gamma P_3
\]

\[
T_5(k) = \left( \frac{P_{\text{atm}}}{P_4} \right)^{-1/\gamma} T_4(k)
\]
A portion of the exhaust gas from one cycle is re-induced
- Causes cycle-to-cycle coupling
- Heat transfer decreases re-induced gas temperature

A simple model for the exhaust gas coupling is:

\[ T_{1, \text{prod}}(k) = \chi T_5(k - 1) \]
- Not very physical (improvement just derived on train from München)
Algebraic manipulation yields a model for peak pressure

\[ P_k = \frac{C_1 + C_2 \alpha_k}{1 + \alpha_k} \left( C_{12} \left( C_1 + C_2 \alpha_{k-1} \right) + C_{13} \left( 1 + \alpha_{k-1} \right) + C_{15} \chi \alpha_k P_{k-1}^{1/\gamma} \right) \]

Where:

- P - peak in-cylinder pressure (measurable)
- \( \alpha \) – molar ratio of inducted products to reactant (input)
- All constants derived from physical values

Cycle-to-cycle dynamics and input appear
Simple Model and Experiment

- Estimates of $\alpha$ can be calculated from experiment
  - Heat transfer $(\varepsilon, \chi)$ calibrated for one operating point
- Model comparison with experiment yields:

<table>
<thead>
<tr>
<th>Case</th>
<th>IVO/EVC</th>
<th>$P_{\max, \text{exp}}$ [atm]</th>
<th>$P_{\max, \text{model}}$ [atm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25/165</td>
<td>59.5</td>
<td>57.4</td>
</tr>
<tr>
<td>2</td>
<td>45/185</td>
<td>52.5</td>
<td>52.4</td>
</tr>
<tr>
<td>3</td>
<td>65/205</td>
<td>44.5</td>
<td>47.4</td>
</tr>
</tbody>
</table>

- Good correlation between experiment and model…
  …but model is not exact (no surprise)
LQR Controller Synthesis

- The model for peak pressure has the basic form:
  \[ P_k = f(\alpha_k, \alpha_{k-1}, P_{k-1}) \]

- A common control approach is to linearize the system model
  - Linearizing about an operating point \((\bar{\alpha}, \bar{P})\) yields:
    \[
    \begin{bmatrix}
    \tilde{\alpha}_k \\
    \beta_k
    \end{bmatrix}
    = \begin{bmatrix}
    0 & 0 \\
    -\frac{c_{23}}{Pc_{20}} & -\frac{c_{21}}{c_{20}}
    \end{bmatrix}
    \begin{bmatrix}
    \tilde{\alpha}_{k-1} \\
    \beta_{k-1}
    \end{bmatrix}
    + \begin{bmatrix}
    1 \\
    -\frac{c_{22}}{Pc_{20}}
    \end{bmatrix} \tilde{\alpha}_k
    \]
    where: \( \beta_k = \left( \frac{P_k - \bar{P}}{\bar{P}} \right) \quad \tilde{\alpha}_k = \alpha_k - \bar{\alpha} \)

- An LQR controller with form:
  \[ \tilde{\alpha}_k = K_1 \beta_{k-1} + K_2 \tilde{\alpha}_{k-1} \]

  … can be developed to minimize:
  \[ J = \sum \left( q \beta_{k-1}^2 + \tilde{\alpha}_k^2 \right) \]

- Use \( q \) to weight error and control input
Closed-loop Control Approach

\[ \overline{P} \]

\[ + \]

\[ \frac{1}{\overline{P}} \]

\[ \beta \]

\[ \tilde{\alpha} \text{ to IVO/EVC map} \]

\[ \tilde{\alpha} \]

\[ \text{IVO} \rightarrow \text{EVC} \rightarrow \text{Engine Cylinder} \]

\[ P_{\text{max}} \]

let: \[ \overline{P} = P_{\text{max,desired}} \]

\[ \frac{1}{z} \]
Control Simulation

- Desired control objectives met:
  - Steady combustion phasing
  - Peak pressure tracking
■ Work output correlates with peak pressure at constant phase
  ● Peak pressure is measurable proxy for work output
From Simulation to Experiment

- Try on single cylinder
  - Premixed propane
  - Constant A/F in intake

- Validation points
  - Peak pressure tracking
  - Phasing
Experimental Implementation

Approach works well for pressure
- Mean tracking
- Dispersion reduced

<table>
<thead>
<tr>
<th>Mean [atm]</th>
<th>Std. dev. [atm]</th>
<th>Pk-to-pk [atm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>desired</td>
<td>Actual</td>
<td></td>
</tr>
<tr>
<td>no control</td>
<td>50.93</td>
<td>2.51</td>
</tr>
<tr>
<td>40</td>
<td>39.95</td>
<td>0.95</td>
</tr>
<tr>
<td>36</td>
<td>35.96</td>
<td>1.11</td>
</tr>
</tbody>
</table>
Experimental Implementation

- Cyclic dispersion reduced with minimal change in IVO/EVC

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<tr>
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<tr>
<td>no control</td>
<td>64.85</td>
<td>7.99</td>
<td>52.4</td>
</tr>
<tr>
<td>65</td>
<td>64.64</td>
<td>3.24</td>
<td>21.75</td>
</tr>
<tr>
<td>no control</td>
<td>63.77</td>
<td>5.58</td>
<td>31.65</td>
</tr>
</tbody>
</table>
What About Phasing?

- Little change in phase
  - Fast transient
    - Predicted by model
    - Residual temperature
  - Slow transient
    - Thermal effects
    - Wall temperature
Comments on Experiments

- Simple controller works well
  - Mean tracking and dispersion reduction
- Implementation is straightforward
  - Tandem shift of IVO/EVC with peak pressure
- Some of this is fortuitous
  - Optimal map might not be tandem IVO/EVC shift
  - Dispersion not always controlled with mean tracking
- Physics-based approach predicts results
  - What about independent control of load and phasing?
Load and Phasing Control

- Why might we want this?
  - Remove transients and aid in SI/HCCI transition

- Basic mathematical relationship
  - Simple model with Arrhenius trigger and IVC input
    
    \[ P_k = f(\alpha_k, \alpha_{k-1}, P_{k-1}, \theta_k, \theta_{k-1}, IVC_k, IVC_{k-1}) \]

    \[ \text{threshold} = \int_{IVC}^{\theta_{comb}} A \exp\left(\frac{E_a}{RT}\right) [C_3H_8]^a [O_2]^b d\theta \]

- Two different approaches
  - Solve simultaneously for valve commands (fast transient)
  - Slowly vary phasing in decoupled manner (slow transient)
Cycle-to-Cycle IVO/EVC/IVC Control

(Shaver, Gerdes and Roelle, Proceedings of the American Control Conference, 2004, Pages 150-155)

- Simulation results
  - Quick response
  - Reasonable timing
  - IVO/EVC no longer move in tandem

- Drawback
  - Computation time
As a start, go after slow transients only

- Keep peak pressure controller, vary phase
- Tighter coupling very possible
Experiments with Load and Phase

Closed-loop control of phasing only

Closed-loop control of phasing and peak pressure
Experiments with Load and Phase

- Simultaneous step changes
  - Phasing and peak pressure

- 4 degree change in phase
  - ~ 30 degree change in IVC

- Change in dispersion
  - Variation higher at later phase

- Very preliminary step
Combined Load and Phase Control

- Possible to control load and phase control
  - Only IVO/EVC/IVC required
  - Fast control works in simulation
  - Slow control works on engine

- Other valve motions are possible
  - Variable lift strategies

- SI to HCCI transition motivates cycle-to-cycle control
  - Model captures basic effects
First look at SI to HCCI Transition
(Roelle, Shaver and Gerdes, Appearing at the 2004 ASME IMECE)

- Slight magnitude offset (need to identify heat transfer)
- Phasing and dynamics captured!
Conclusion

- HCCI is amenable to model-based control
  - Mean tracking
  - Reduction in cyclic dispersion

- Benefits of a solid HCCI controller design
  - Broader operating region and precise control
  - Minimal valve actuation
  - Combined strategy for load tracking and transition

- When viewed as part of closed-loop system, HCCI can be well-behaved
Future Work

- More experimental testing
  - Investigate increase in stable operating regime
  - Validate combined load and phasing control
  - Test SI-HCCI transition strategies

- Better algorithm development
  - Best controller for combined load and phasing
  - Integrated transition controller

- Bring a new engine testbed on line
  - Volvo D1 dedicated to HCCI control