Physics-based Control of Residual-Effected HCCI Engines

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Outline

- Challenges/Opportunities for control in HCCI
  - Cyclic coupling
  - Lack of combustion trigger

- Simulation modeling of residual affected HCCI
  - Review of approach: Basic model and ignition criteria
  - Added capabilities: Transients, mode transitions & gasoline

- Control model and controller design
  - Review of approach
  - Added capabilities: direct control of IMEP & phasing
Challenges/Opportunities in HCCI with VVA

- Variable valve actuation
  - Valves are only input: IVO/EVC/IVC
  - Fuel is another input: fixed equivalence ratio in intake

- Cycle-to-cycle coupling through exhaust gas

- No direct initiator of combustion
  - Dependent on kinetics: reactant concentrations, temperature & amount of compression
  - Transients & mode transitions complicate this

- Modeling and control work must account for:
  - Coupling and ignition via kinetics
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 that capture behavior most relevant for control
  ● Cyclic coupling
  ● Combustion phasing
  ● In-cylinder pressure evolution
  ● Work output

■ Sophistication in proving stability, boundedness, control design, etc.
1st law analysis of cylinder and exhaust manifold
Multi-cycle HCCI Simulation Model

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- Steady state 1D compressible flow relations
Multi-cycle HCCI Simulation Model

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- Heat transfer
  - In-cylinder (modified Woschni)
    - Ref: Chang et al. 2004
  - Exhaust manifold
Multi-cycle HCCI Simulation Model

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- Combustion model
  - Wiebe function
  - What do we use as a trigger for HCCI combustion?
Integrated Arrhenius Rate Equation

- Simple model for start of combustion
  - 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
  - \(a, b\) and \(E_a\) from published experiments

- Contributions from temperature, compression & concentration captured

- Different from knock integral:
  - In knock integral \(a = b = 0\)
Integrated Arrhenius Rate

- Set threshold at one operating point…
Set threshold at one operating point…
…and pressure, phasing & IMEP at all points is captured
Simulation Model: Steady State Propane

Note: can vary RMF without much change in phasing
- Integrated Arrhenius model captures this
- Can find (IVO/EVC) valve manifold that maintains nearly constant phasing while varying RMF
Steady state behavior with propane captured

What about:
- Gasoline
- Transients
- SI-to-HCCI mode transitions

Can modeling approach capture these cases?
Simulation Model: Gasoline

- Simple model captures behavior most relevant for control
  - In-cylinder pressure evolution
  - Combustion phasing
  - Work output

- This is not a big surprise:
  - Ignition delay models of complex fuels have same form as integrated Arrhenius (He et al. 2003)
Simulation Model: Transients

- **1st operating point has higher steady state temperature than 2nd**

- The elevated exhaust temperature advances combustion process during transition

- As exhaust temperature decreases, behavior reaches new steady state
Simulation Model: Transients

- Simple model captures the coupling and ignition behavior during transition.
- As $\Delta T_{\text{exht}}$ increases, effect increases.
Mode Transition

- What will happen during a SI-to-HCCI mode transition?

- SI exhaust temperature are typically substantially higher than HCCI

- We would expect to see a more pronounced effect
SI to HCCI Mode Transition Simulation

- Mode transition captured
- Coupling same: natural extension of HCCI coupling
Results from Simulation modeling

- Aspects most relevant for control captured with simple simulation model:
  - Cyclic coupling
  - Combustion phasing
  - Work output & in-cylinder pressure evolution

- Approach can handle:
  - Steady-state behavior w/ propane and gasoline
  - Transients
  - SI-to-HCCI mode transitions
A Simple Control Strategy

- Intuition gained from simulation work: can use VVA to independently:
  - Vary inducted composition (via IVO and EVC)
  - Vary effective compression ratio (via IVC)

- Control model:
  - Input: $\alpha = N_p/N_r$ (composition)
  - Input: IVC (amount of compression)
  - Output: peak pressure or load
  - Output: combustion phasing

- Step through process to determine model
Assumptions:
- Induction: atmospheric pressure
- Full mixing
- Isentropic compression & expansion
- HCCI is fast: constant volume combustion
- In-cylinder heat transfer (in cylinder): % of LHV
- Exhaust manifold Heat transfer: convective
The control model takes the form:

\[ P_k = f(\alpha_k, \alpha_{k-1}, P_{k-1}, \theta_k, \theta_{k-1}, IVC_k, IVC_{k-1}) \]

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

- P - peak pressure
- \( \theta \) – crank angle at combustion
- \( \alpha \) – composition (VVA controllable input)
- IVC (VVA controllable input)
- All constants derived from physical values

Control model still captures
- Cyclic coupling
- Ignition via kinetics
Peak Pressure Control w/ Constant Phasing

- Fix IVC
- pick IVO/EVC manifold to vary $\alpha$, with:
  - $\sim$ constant phasing (a “static” approach to treating phasing)

\[
P_k = f(\alpha_k, \alpha_{k-1}, P_{k-1}, \theta_k, \theta_{k-1}, IVC_k, IVC_{k-1})
\]

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

\[
P_k = f(\alpha_k, \alpha_{k-1}, P_{k-1})
\]

- Can then linearize model and synthesis controller
Experimental Control of Peak Pressure

- Accurate control of peak pressure
  - Mean tracking
  - Dispersion reduction

- Little change in phase
  - Fast transient
    - Residual temperature
  - Slow transient
    - Wall temperatures

- What about direct control of IMEP?
Direct IMEP Control

- A very simple model for IMEP can be formulated:

\[
IMEP = \frac{P_{atm} V_{IVC}^\gamma \left( V_{TDC}^{1-\gamma} - V_{IVC}^{1-\gamma} \right) + P_{pk} V_{pk}^\gamma \left( V_{EVO}^{1-\gamma} - V_{pk}^{1-\gamma} \right)}{1-\gamma}
\]

- With IVC and phasing fixed, IMEP is linearly dependent on peak pressure:
  - So: IMEP control is extension of peak pressure control
  - Can use similar control strategy
Experimental IMEP Control

- Rapid tracking & dispersion reduction
- Manageable valve movements
- We can control IMEP, while keeping phasing roughly constant
Comments on Experiments

- Simple physics-based controller works well
  - Mean tracking & dispersion reduction:
    - peak pressure
    - IMEP
  - Phasing fairly constant
  - Implementation is straightforward

- What about independent control of IMEP & phasing?
Peak Pressure and Phasing Control

- Recall: control model
  \[ P_k = f(\alpha_k, \alpha_{k-1}, P_{k-1}, \theta_k, \theta_{k-1}, IVC_k, IVC_{k-1}) \]
  \[ \text{threshold} = \int_{IVC}^{\theta_{comb}} A \exp\left( \frac{E_a}{RT} \right) \left[ C_3 H_8 \right]^a \left[ O_2 \right]^b d\theta \]

- Add a control input: IVC (effective comp. ratio)

- Two different approaches
  - Separate linear controllers for peak pressure and phasing
  - Solve two nonlinear equations simultaneously
    - Dynamic Feedback Linearization
Decoupled Peak Pressure and Phase Control

- Maintain cycle-to-cycle peak pressure controller, vary phase more slowly.
Experiments with Load and Phase

- Approach works
- Step change
  - Phasing
- Change in dispersion
  - Variation higher at later phase
Experiments with Decoupled Control

- Approach works
- Simultaneous step changes
  - Phasing and peak pressure
- 4 degree change in phase
  - ~ 30 degree change in IVC
Dynamic Feedback Linearization

- Simulation results
  - Fast cycle-to-cycle response

- Drawback
  - Computation time

- Future work:
  - Finding appropriate balance between complexity & capability
Conclusion

- Key behaviors captured in both simulation and control:
  - Cyclic coupling through the exhaust gas temperature
  - Ignition via chemical kinetics:
    - reactant concentration
    - temperature
    - effective compression ratio

- Simulation modeling extended to handle:
  - Gasoline
  - HCCI transients
  - SI-to-HCCI mode transitions

- Physics-based control of:
  - Peak pressure
  - IMEP
  - Peak pressure and phasing
Future Work

- Extension of techniques to independent control of IMEP and phasing on cycle-to-cycle basis

- Control of SI-to-HCCI transitions

- Investigate use of variable lift strategies for control