High-Dilution Stoichiometric Gasoline Direct-Injection (SGDI) Combustion Control Development

Project ID # ACE090

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High-dilution SGDI project overview

Timeline
• Evolution of a project that began in 2011
• Current trajectory began in 2013

Budget
• FY 2014: $300k
• FY 2015: $200k

Barriers (MYPP §2.3.1 A, D)
• Lack of fundamental knowledge of advanced engine combustion regimes
• Lack of effective engine controls

Partners/Interactions
• Collaborations
  – Bosch
  – National Instruments
  – Argonne National Laboratory
• Regular status reports to DOE
Objective: Develop advanced control strategies to extend SI dilution limits

- Project Objective
  - Address barriers to the VTO goal of improving light-duty vehicle fuel economy by developing control strategies that enable high-efficiency, high-dilution, gasoline direct-injection (GDI) engine operation
  - Extend dilution limit to enable greater efficiency gains in modern GDI engines, leading to increased vehicle fuel economy

- FY 14-15 Objectives
  - Characterize cyclic variability for external EGR operation
  - Evaluate effects of data quality on symbol-sequence analysis
  - Develop next-cycle control methodology to reduce cyclic variability
  - Implement next-cycle controls on engine and evaluate efficacy

Goal of Advanced Combustion Engines R&D
“By 2015, improve the fuel economy of light-duty gasoline vehicles by 25 percent and of light-duty diesel vehicles by 40 percent, compared to the baseline 2009 gasoline vehicle.” (MYPP 2011-2015 §2.3.1)
All tracked milestones have been completed or are on-track

<table>
<thead>
<tr>
<th>Month/Year</th>
<th>Milestone</th>
<th>Status</th>
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<tbody>
<tr>
<td>12/2013</td>
<td>Characterize sensitivity of control parameters on data sampling rate and quality</td>
<td>Completed</td>
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<tr>
<td>03/2014</td>
<td>Demonstrate automatic cylinder balancing which will be integrated with next-cycle control in future milestone</td>
<td>Completed</td>
</tr>
<tr>
<td>06/2014</td>
<td>Demonstrate next-cycle control of engine based on prior-cycle events</td>
<td>Completed</td>
</tr>
<tr>
<td>09/2014</td>
<td>Demonstrate potential of next-cycle control on combustion stability, engine efficiency, and dilution limit extension</td>
<td>Completed</td>
</tr>
<tr>
<td>06/2015</td>
<td>Demonstrate impact of combined control strategies on EGR dilution limit extension</td>
<td>On Track</td>
</tr>
<tr>
<td>09/2015</td>
<td>Demonstrate applicability of next-cycle control strategy to homogeneous lean combustion</td>
<td>On Track</td>
</tr>
</tbody>
</table>
Advanced controls use deterministic behavior to reduce cyclic variability

- Combustion instabilities at the dilution limit have deterministic structure combined with stochastic noise

**Determinism implies controllability**

- Leverage ORNL’s extensive background in identifying dynamical structure in noisy and chaotic time series
- Utilize tools from nonlinear dynamics and information theory to predict and control deterministic variations
- Enable operation at the “edge of stability”
Symbol-sequence statistics analysis finds order in chaos

- Method:
  - Partition data into discrete bins
    - Each bin is labeled with a “symbol” or “letter”
  - Identify sequences of a given number of cycles
    - These symbol sequences can be thought of as “words” made up of the symbolic “letters”
  - Detect patterns by identifying words that occur frequently

- This information will be used to enable online control of cyclic variability

Example time series with binary symbol partition

Symbol sequence histogram with 2 symbolic letters and a word length of 6

Alternating high/low-energy cycles
Experimental platform: 4-cylinder GDI engine with cooled EGR

- GM LNF 2.0L turbocharged GDI engine
  - Modified by Bosch for DOE FFV optimization program
  - Outfitted by ORNL with external cooled EGR loop
- NI (Drivven) Engine Controller
  - Allows fully customizable engine controls
  - Capable of next-cycle or same-cycle controls

<table>
<thead>
<tr>
<th>Engine Specifications</th>
<th>Stock</th>
<th>Modified</th>
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<tbody>
<tr>
<td>Bore</td>
<td>86 mm</td>
<td></td>
</tr>
<tr>
<td>Stroke</td>
<td>86 mm</td>
<td></td>
</tr>
<tr>
<td>Compression ratio</td>
<td>9.50:1</td>
<td>10.67:1</td>
</tr>
<tr>
<td>Ignition coil energy</td>
<td>80 mJ</td>
<td>100 mJ</td>
</tr>
<tr>
<td>Maximum cylinder P</td>
<td>100 bar</td>
<td>130 bar</td>
</tr>
<tr>
<td>Induction</td>
<td>Turbocharged</td>
<td></td>
</tr>
<tr>
<td>Fuel system</td>
<td>Wall-guided GDI</td>
<td></td>
</tr>
</tbody>
</table>
Accomplishments—Overview

• Built further understanding of cycle-to-cycle dynamics: needed to develop effective control strategies
  – Ability to use production-viable sensors: data quality study
  – Effects of control parameters
    • Spark re-strike study
    • Collaborated with Argonne National Laboratory on study of effects of control perturbations on dilute combustion
  • Implemented initial symbol-sequence-based control strategy on the engine
    – Control strategies currently being refined and improved based on information gained
    – Adapting symbol-sequence analysis method to account for dual feedback timescale with external EGR loop and build symbolic words based on appropriate feedback cycle history
Laboratory-quality data is unlikely to be available in production: how does this impact advanced controls?

- Effects of data quality reduction were evaluated in post-processing.
- Data from two operating conditions considered:
  - Low-COV: 2000 rpm, 4 bar BMEP, φ = 1 (COV = 1.7%) — General trends
  - High-COV: 2000 rpm, 4 bar BMEP, φ = 0.7 (COV = 37.7%) — Symbolic analysis
- Errors imposed on cylinder pressure data
  - TDC offset, Pegging offset, Reduced crank-angle resolution, Random noise
- Metrics evaluated
  - IMEP, Cumulative heat release (HR), Peak pressure, CA10/50/90, Max pressure rise rate (MPRR)
Symbol sequence analysis is effective even with poor-quality data

- Data quality reduction has significant impact on combustion metrics, e.g.
  - TDC offset: 4.5% error in IMEP per °CA
  - Reduced resolution: 2.2% error in IMEP and 3.8% error in HR per 1° resolution

- Symbol sequence analysis is robust even when analyzing time series of these erroneous metrics
  - Overall structure of histogram unchanged
  - Individual words also detected with similar frequency

Multiple spark strategy can qualitatively change cyclic dynamics

- Adding a restrike spark helps reduce misfire events
  - Converts misfires to partial burns
  - Impact initially grows with restrike delay

- After some threshold, retarding the restrike further is counter-productive
  - Increased COV and misfires
  - Collapse of deterministic structure – largely stochastic variations
  - Unclear so far whether cause is inherent in late restrike or due to increased variability in timing due to constant time restrike delay in ms rather than crank angle
Effects of cycle-to-cycle perturbations of ignition timing and fuel quantity vary with dilution

- Experiments at ANL perturbing ignition timing ($\pm x^\circ$) and injection quantity ($\pm x\%$) every-other-cycle
- Analysis at ORNL using nonlinear dynamics tools
  - Effects of ignition perturbations are suppressed by dilution
    - Longer burn duration necessitates earlier spark timing
    - Less sensitivity to small changes in this region
  - Effects of injection perturbations are amplified for lean operation
    - Ignition and flame propagation properties nonlinearly dependent on mixture composition for dilute combustion
    - Next-cycle feedback from residual fraction is predominant for lean operation – synchronous with perturbations
    - For EGR operation, dominant feedback is longer-timescale due to external EGR loop – not synchronous with perturbations

Symbol sequence analysis of 50% MFB location for ignition perturbation at baseline conditions as well as lean ($\lambda=1.6$) and 21% EGR dilute operation

Effects of cycle-to-cycle perturbations of ignition timing and fuel quantity vary with dilution

- Experiments at ANL perturbing ignition timing (±x°) and injection quantity (±x%) every-other-cycle
- Analysis at ORNL using nonlinear dynamics tools
  - Effects of ignition perturbations are suppressed by dilution
    - Longer burn duration necessitates earlier spark timing
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Next-cycle control strategy: use symbol sequence analysis to correct undesirable trajectories

Crankshaft Encoder → Cyl P → Combustion Analysis

Symbolic Analysis

Sensitive to Data Quality

Cycle Cumulative Heat Release (Time Series)

Controller

Next-Cycle Prediction

Insensitive to Data Quality

ACCOMPLISHMENTS (6/7)
Symbol sequence method has been modified for dual-timescale feedback

- External EGR: Delayed feedback
- Internal residual: Prior-cycle dominant

Build symbolic “words”

Time series of cumulative heat release

Heat Release (J)

Engine Cycle
Symbol sequence method has been modified for dual-timescale feedback

- Initial results indicated method not sufficiently effective when building symbolic words for a single cylinder
- Need to modify to incorporate multi-cylinder feedback history, accounting for firing order (currently in progress)

Recurring patterns indicate deterministic trajectories

External EGR: Delayed feedback
Internal residual: Prior-cycle dominant

Build symbolic “words”

111100
000110
Reviewer comments from FY 2014

Positive comments

“The reviewer exclaimed that it was about time someone did this work. The reviewer remarked that it was an exciting chance to do something about the stability limit.”

“The reviewer noted good progress by the project team on a difficult problem. The project team has created a good test bed and the necessary infrastructure to do some great work.”

Responses to reviewer comments/suggestions

Reviewers inquired whether cylinder pressure was required for optimal control, and inquired if crankshaft speed or some other feedback mechanism could be used.

We believe crankshaft speed or other metrics would be suitable: results of a data quality study motivated by this question are included here and were published earlier this FY, and there is an existing patent (Ford & ORNL, #5,921,221) based on earlier lean combustion work that utilized crankshaft acceleration.

Reviewers expressed a desire to see more collaborations, especially from an OEM’s controls experts.

This project has received general directional input from industry via presentations at the ACEC Tech Team and such forums, but we would welcome more direct OEM involvement.

Reviewers asked whether the EGR path length results are as applicable at more moderate EGR rates with low COV or only for the extreme case with misfires.

This is a good question, and one we are currently working to answer. Experiments using fast EGR sensing technology developed in a separate ORNL project (Partridge # ACE077) are currently underway to determine the extent to which the temporal resolution of combustion products is maintained at more moderate EGR levels where misfires do not occur.
Collaborations

• National Instruments Powertrain Controls (Drivven)
  – Support of next-cycle and same-cycle controls development
  – In talks to exchange data and collaborate on joint publications

• Argonne National Laboratory
  – Collaboration on analysis of effects of control perturbations in dilute SI combustion
  – Joint paper to be published later this FY

• Robert Bosch LLC
  – High-compression GDI engine customized in previous DOE program
  – Provided engine and ECU with calibration-level access

• ORNL–Cummins Combustion CRADA
  – High-resolution EGR measurements
Remaining Challenges and Barriers

- Need to improve prediction for external EGR
  - Interleaved multi-cylinder, multi-timescale symbolic words
  - Model-based prediction

- Need to refine and improve control strategies
  - Determine efficacy of enhanced symbol-sequence based control
  - Integrate online model-based control
  - Determine efficacy at “edge of stability”
  - Extend to transient operation

- Evaluate applicability to lean-burn GDI
Future Work (3-Year Plan Reviewed by ACEC Tech Team 9/11/2014)

• Remainder of FY 2015
  – Evaluate EGR feedback dynamics for moderate EGR levels (no misfires)
  – Continue development of next-cycle control strategies
    • Improve strategies for high-EGR operation
    • Evaluate application to lean-burn GDI
    • Demonstrate dilution limit extension

• FY 2016
  – Development of low-order models for improved prediction
    • Extension of prior ORNL efforts for lean combustion to high-EGR operation
    • Informed by results from ORNL HPC work (Edwards # ACE017)
  – Continued next-cycle control strategy development

• FY 2017
  – Evaluate potential for same-cycle control strategies
    • Detect and correct for misfires or slow burns during combustion
    • Possible future applications for other combustion modes at the edge of stability
  – Plans will evolve based on FY 15-16 results
### Summary

#### Relevance
- Dilute combustion enables significant fuel efficiency gains in modern SI engines, but is limited by cyclic variability

#### Approach
- Use tools from nonlinear dynamics and information theory to take advantage of deterministic effects and develop active control strategies that bring order out of chaos, reducing cyclic variability and extending practical dilution limits

#### Accomplishments
- Built further understanding of cycle-to-cycle dynamics that will be used to develop improved control strategies
- Implemented initial symbol-sequence-based control strategy on the engine
- Adapted symbol-sequence analysis method to account for dual feedback timescale with external EGR loop

#### Collaborations
- Collaborating with industry on high-EGR control system development

#### Future Work
- Implementing next-cycle control strategies to enable operation on the “edge of stability”
Simple representation of the onset of cycle-to-cycle instabilities

- Driven by stochastic (in-cylinder variations) and deterministic (cycle-to-cycle coupling) processes
- Instabilities may be “short” or “long”\(^1\) timescale
  - “Short” refers to a few successive cycles
  - “Long” refers to 10s-100s successive cycles
- Practical implementations operate well away from the edge of stability to avoid unintended excursions
- Advanced controls could enable operation at the “edge of stability”
  - Requires a detailed understanding of instability mechanisms

Nonlinear dependence of combustion on composition causes chaotic behavior

- Flame speed dependence on \( \phi \) is highly nonlinear
  - System is very sensitive to small variations in composition
  - Can take advantage of this to enable active control

\[
S_L = S_{L0} \left( \frac{T_u}{T_0} \right)^\alpha \left( \frac{P}{P_0} \right)^\beta \left( 1 - 2.1Y_{dil} \right)
\]

\[
S_{L0} = B_M + B_2 (\Phi - \Phi_M)^2
\]

\[
\alpha = 2.18 - 0.8(\Phi - 1)
\]

\[
\beta = -0.16 + 0.22(\Phi - 1)
\]


Long time-constant combustion instabilities observed for high-EGR operation

• Combustion instabilities
  – Alternates between high-quality combustion and misfires
  – Period on the order of 10s of cycles
  – Variations synchronized across all 4 cylinders

• External EGR loop feedback dominates over internal residuals
  – Period of oscillations is due to flow through EGR loop
  – Recirculated exhaust from misfire cycles provides extra fuel and air
  – Recirculated exhaust from high-energy cycles provides only inert diluent
Fast EGR Measurement Probe

Multi-Color Multi-Species EGR Probe

- Measures CO₂, H₂O, T & P
- Leverages ORNL–Cummins CRADA & SuperTruck
  - CRADA
    - Original EGR Probe development
  - SuperTruck
    - H₂O diagnostic development at Purdue
  - CRADA & SuperTruck
    - 4-probe multi-plex system
    - Combined CO₂–H₂O probe instrument

- Improved analysis
  - Iterative baseline fit
  - Absorption profile fit to theory (vs. integration & calibration-factors)
  - Shifted-sawtooth laser ramp for real-time background subtraction
  - Improved wavelength calibration
  - 5kHz rate (200μs, 2.4° CA at 2k RPM)
ANL Single-Cylinder Engine Setup for Perturbation Experiments

- Typical SI combustion chamber design
  - 140° pent roof head, flat piston top, central spark plug and injector

- External high pressure gasoline pump
  - Up to 200 bar injection pressure

- High Speed Secondary Coil Voltage
  - ~1 nanosecond breakdown phase
  - 2.4 kV in-cylinder breakdown

GDI Engine Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Displacement</td>
<td>0.626 L</td>
</tr>
<tr>
<td>Bore/Stroke</td>
<td>89/100.6 mm</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>12.1</td>
</tr>
<tr>
<td>Intake Valve MOP</td>
<td>100 °CA ATDC</td>
</tr>
<tr>
<td>Exhaust Valve MOP</td>
<td>255 °CA ATDC</td>
</tr>
<tr>
<td>GDI Injector</td>
<td>6 hole, solenoid</td>
</tr>
<tr>
<td>Injection pressure</td>
<td>150 bar</td>
</tr>
<tr>
<td>Spark Plug</td>
<td>NGK-R dual fine wire, 0.7 mm gap</td>
</tr>
<tr>
<td>Fuel</td>
<td>EPA Tier II EEE</td>
</tr>
</tbody>
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