Enabling High Efficiency Combustion through an Improved Understanding of Cyclic Dispersion

Robert Wagner
Fuels, Engines, and Emissions Research Center
Energy and Transportation Science Division

2011 ERC Symposium
Future Engines and Their Fuels

June 8, 2011
University of Wisconsin
Outline

• Stability challenges

• Control opportunities
  – Operation near the “edge of stability”
  – Transitioning combustion modes
  – Avoiding abnormal combustion events

• Forward directions
Outline

• Stability challenges

• Control opportunities
  – Operation near the “edge of stability”
  – Transitioning combustion modes
  – Avoiding abnormal combustion events

• Forward directions
Motivation and Challenges of High Efficiency Clean Combustion

**Motivation ➤ EFFICIENCY**

- More rapid energy release
- Reduction in heat transfer losses
- Reduction in NOx and soot emissions – less aftertreatment to meet emissions regulations

**Challenges**

- **Precise control of boundary conditions**
  Turbo-machinery, variable valve actuation, heat exchangers
- **Higher in-cylinder peak pressures**
  Materials
- **Improved fuel injection technology**
  Injector architecture, faster response
- **Increase in HC, CO emissions**
- **Stability**
  Cyclic dispersion, adaptive controls, advanced sensors, etc.

---

Motivation diagram showing the local equivalence ratio and temperature in the context of high efficiency clean combustion.
Stability and control are potential roadblocks to the most efficient implementation of many advanced combustion concepts

- Practical implementations operate well away from the edge of stability to avoid unintended excursions.
- Cyclic dispersion driven by stochastic (in-cylinder variations) and deterministic (cycle-to-cycle coupling) processes.
  - Very nonlinear relationship for conditions consistent with many LTC concepts.
  - Deterministic mechanisms act as nonlinear amplifier to stochastic variations.
- Further complicated by cylinder imbalances.
  - Cyclic dispersion may amplify cylinder-to-cylinder imbalances.
- Improved control will require an improved understanding of instability mechanism.

Unintended excursions to the unstable region may result in misfires and very strong “rebound” events which could damage the engine and/or catalyst system.
Advances in sensor technology and onboard computer power are expanding the possibilities for high speed predictive control

**Measurement**
- In-cylinder pressure
- Ionization
- Acoustic
- Other

**Analysis**
- Pattern recognition
- Prediction
- Modeling

**Control**
- Avoid certain states
- Short- and long-time scale feedback perturbations
- Pro-active

---

Managed by UT-Battelle
for the U.S. Department of Energy
Adaptive controls must compensate for prior cycle memory, stochastic influences, and speed/load demands which impact the current combustion event.
**EXAMPLE** Even simple systems can have very complicated dynamic behavior

The Logistic Equation is given by:

\[ x(i+1) = f[x(i)] = k x(i) [1 - x(i)] \]

For \( k = 3.2 \), the system exhibits complex behavior. The diagram illustrates the development of higher order periods and deterministic chaos as the parameter \( k \) changes.
Stochastic noise complicates the system response, but underlying map is still recoverable (and necessary for control)

Logistic Equation

with random perturbations on $k$

$x(i+1) = a_0 + a_1 x(i) + a_2 x(i)^2 + \ldots + a_n x(i)^n$

Underlying map reconstructed, even with high levels of parametric noise, assuming form of $n^{th}$ order polynomial
Outline

• Stability challenges

• Control opportunities
  – Operation near the “edge of stability”
  – Transitioning combustion modes
  – Avoiding abnormal combustion events

• Forward directions
Spark-ignition combustion becomes unstable with lean operation (or high levels of dilution)

φ = 1.0

Heat Release (i+1)

Heat Release (i)

More Lean (higher dilution)

φ = 0.72

Heat Release (i+1)

Heat Release (i)

Equivalence Ratio

Experimental Data

Example of map reconstruction and identification of fixed points

Map reconstructed assuming form as \( hr(i + 1) = b_0 + b_1 hr(i) + b_2 hr(i)^2 + \ldots + b_n hr(i)^n \)
Same approach used to reconstruct the bifurcation diagram

Understanding the dynamics may allow operation closer to the “edge of stability”.

Wagner et al. SAE 2001-01-3559.
Simple model captures nature of lean combustion instabilities and assists with physical interpretation of data.

Cylinder-to-cylinder differences become more of an issue for operation near a stability limit

- Small differences may result in different dynamic behavior for each cylinder.
- An abnormal combustion event in one cylinder may influence other cylinders.

Ford V8, $\phi = 0.66$
Low-order maps reveal cylinder-to-cylinder differences in dynamic state

GM Quad 4, φ = 0.6

Air Flow
Cylinders “communicate” with each other and tend to synchronize under unstable conditions

- Symbol sequence analysis used to resolve dynamical relationships between cylinders.
- Original time series transformed into sequence of discretized symbols.
- Transformation aids in detecting and characterizing nonrandom patterns, even in the presence of high levels of noise.

Data partitioned into discrete bins (binary example shown)
Symbol analysis used to construct *synchograms* to observe evolution of joint cylinder bifurcations and correlation in time

GM Quad 4, $\phi = 0.59$

---

Uncorrelated
(F1, F3)

Anti-Correlated
(F2, F3)
General observations on synchronization

- Synchronization occurs frequently with bifurcation of 2 or more cylinders.
- One cylinder can act as a driver for others.
- Synchronization occurs episodically (correlations persist for long times and suddenly shift).
- Probably associated with pressure waves in intake/exhaust manifolds, fueling interactions, “common noise”
Example application of adaptive control by ORNL and Ford Motor Company on an 8-cylinder SI engine

Demonstrated significant improvements in engine stability for idle and low-load conditions (U.S. Patent 5,921,221).
Outline

• Stability challenges

• Control opportunities
  – Operation near the “edge of stability”
  – Transitioning combustion modes
  – Avoiding abnormal combustion events

• Forward directions
Spark assist is potential mechanism to control and transition HCCI for more widespread use

Motivation

- Use of Homogeneous Charge Compression Ignition (HCCI) combustion has potential for significant reduction of NOx emissions and increased fuel efficiency.
- Unstable transition between SI and HCCI operation is challenge for HCCI implementation.

Objective

- Improve understanding of instability mechanism during transition from SI to HCCI.
- Make use of engine-based, dynamic combustion measurements to quantify effective global kinetic rates.
- Develop simplified cyclic combustion models for rapid simulation, diagnostics, and controls.

HCCI Description

- Pre-mixed, pre-heated fuel-air charge
- Ignition very dependent on temperature and species
- Uniform, spontaneous combustion without flame front

Figure adapted from GM images by K. Dean Edwards, ORNL.
Distinct combustion modes observed during transition from SI to HCCI

Nominal operating conditions 1600 rpm, 3.4 bar IMEP with no feedback control

- **Conventional**: 13% Internal EGR
- **Transition**: Requires spark and exhibits multiple combustion modes including hybrid modes
- **HCCI**: No spark required
- **Spark Assisted HCCI**: Requires spark to operate

Discontinuity between transition range and spark assisted HCCI

Wagner et al. SAE 2006-01-0418 / Bunting et al., SAE 2006-01-0872
Bifurcation diagram further illustrates unstable transition from conventional SI to HCCI combustion

- Combustion evolves between two distinct states representing SI and HCCI combustion.
- Ignition and propagation processes for both SI and HCCI are highly nonlinear.
- Transition region requires spark ignition.

Better understanding of dynamics necessary to navigate transition region and speed/load transients.

Is there any reason we would want to operate within this region?
Heat release rates reveal that desirable and undesirable sequences involve different mixtures of SI-like and HCCI-like combustion.

- Different forms of combustion visited during unstable excursions.
- Possibilities include flame propagation, HCCI, and hybrid modes.
Operation at an intermediate dilution level could allow for HCCI-like benefits with reasonable pressure rise rates

- Multiple reaction modes appear to be occurring during a single combustion event.
- Tension between competing modes leads to characteristic patterns of instability.
Heat release profiles associated with fixed points are much different than observed for pure SI or HCCI.

- Unstable period-1 fixed point is possible control zone.
- Trajectory in/out of “stable” zone appears predictable.
- May be possible to rate shape heat release through trajectory control.
Opportunity for control is to exploit naturally occurring hybrid states which exhibit an optimal balance of SI and HCCI

Unstable 3-state pattern due to excursions in SI HCCI balance

Optimal balance of SI & HCCI occurs naturally but is not stable

Frequent recurrence of optimal state suggests potential control target

Patterns are complex but not random and are short-term predictable.
Combustion variations under intermediate dilution conditions exhibit recurring multi-cycle sequences

Some burn variations are almost periodic and large in amplitude (e.g., a 3-cycle sequence)

Combustion often stabilizes near one state for several cycles but eventually diverges

When combustion finally diverges from this 'nominal' state, it does so in specific ways
Simple physical model yields integrated HR patterns similar to those observed in experiments

- Tracking cycle-by-cycle events reveals switching between two distinct HCCI-like combustion modes.
- Hypothesize switch mechanism depends on shifts in residual composition.
- Random noise added to EGR fraction to simulate stochastic in-cylinder processes.

Such models are expected to be useful for short-term prediction and correlation of instability patterns with fuel properties and chemistry.

Outline

• Stability challenges

• Control opportunities
  – Operation near the “edge of stability”
  – Transitioning combustion modes
  – Avoiding abnormal combustion events

• Forward directions
Abnormal combustion events observed for low-speed high BMEP operation

Often referred to in the literature as Low Speed Pre-Ignition (LSPI) or Superknock

SwRI Example LSPI* Point

- 1250 rpm @ 12.5 bar
- Stoichiometric operation with no dilution.
- 30,000 engines cycles necessary to observe multiple occurrences.

Data courtesy of Manfred Amann and Terry Alger from Southwest Research Institute.
Experimental data illustrating the onset of abnormal combustion

- Each pre-ignition event consists of 1-20 consecutive engine cycles before returning to normal operation.
- Engine damage may be caused within few engine cycles depending on the severity of the events.
Advanced time-series analysis techniques used to find patterns with purpose to develop methods for LSPI avoidance

- Example methods include data symbolization (coarse-grained inter-cyclic pattern identification) and phase-space reconstruction techniques (intra-cyclic dynamic evolution).

- Phase-space reconstruction shows pronounced prior-cycle deviations, and the evolution of the LSPI event is highlighted early.

Analysis by Charles Finney, ORNL.
Outline

• Stability challenges

• Control opportunities
  – Operation near the “edge of stability”
  – Transitioning combustion modes
  – Avoiding abnormal combustion events

• Forward directions
On-going and Future Research

- **Toolkit development for assessing, predicting, and controlling unstable behavior**
  - Algorithms based on well-understood principles from nonlinear dynamics and information theory.
  - Includes addressing amplification of cylinder-to-cylinder dynamics due to high cyclic dispersion.

- **Abnormal combustion avoidance**
  - Informal collaboration with SwRI for prediction and avoidance of undesirable excursions.

- **Reactivity Controlled Compression Ignition (RCCI) combustion**
  - Operational space bounded by regions of instability.
  - Instabilities strongly affected by dilution level, intake temperature, mixing, etc.
  - Cylinder-to-cylinder imbalances are exacerbated by cyclic dispersion.
  - Predictive control under development and based on better understanding of instability mechanisms and cycle-to-cycle interactions.
Final Thoughts

- A dynamic perspective provides new insight into combustion instabilities and control opportunities.
  - Impact of stochastic processes on combustion stability a high priority topic in upcoming DOE predictive simulation initiative.
  - Deterministic processes also of extreme importance for operation near “edge of stability”.
- Potential benefits:
  - Operation closer to the edge of stability.
  - More efficient mode transitions.
  - Operation within inherently unstable regions for efficiency/emissions benefits.
  - Prediction and avoidance of abnormal destructive combustion events (e.g., Superknock).
- Control comments:
  - Reduce stochastic variations as much as possible.
  - Many useful tools from nonlinear dynamics and information theory.
  - Low-order qualitative models able to predict the complex dynamics observed experimentally.
  - Appropriate control target is stable dynamic manifold region as opposed to a point.
Acknowledgements

Special thank you to the DOE for funding portions of this research, numerous ORNL staff for valuable contributions to this topic, and SwRI for sharing LSPI data.