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AN APPROACH FOR INVESTIGATING ADAPTIVE CONTROL STRATEGIES TO IMPROVE COMBUSTION STABILITY UNDER DILUTE OPERATING CONDITIONS

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ABSTRACT

Dilute operation of internal combustion engines through lean fueling and/or high levels of exhaust gas recirculation (EGR) is frequently employed to increase fuel efficiency, reduce NO_x emissions, and promote enhanced combustion modes such as HCCI. The maximum level of dilution is limited by the development of combustion instabilities that produce unacceptable levels of cycle-to-cycle combustion variability. These combustion instabilities are frequently stimulated by the nonlinear feedback associated with the residual and recirculated exhaust gases exchanged between successive cycles. However, with the application of adaptive control, it is possible to limit the severity of the combustion variability and regain efficiency and emission reduction benefits that would otherwise be lost. In order to better characterize the benefits of adaptive control, we have employed a two-zone phenomenological combustion model to simulate the onset of combustion instabilities under dilute operating conditions and illustrate the impact of these instabilities on emissions and fuel efficiency. The two-zone in-cylinder combustion model is coupled to a WAVE engine-simulation code, allowing rapid simulation of several hundred successive engine cycles with many external engine parametric effects included. By applying adaptive feedback control to the WAVE model, we demonstrate how mitigation of the extreme combustion events can result in improved efficiency and reduced emissions levels. We expect that this approach can be used to estimate the potential benefits of implementing adaptive control strategies on specific engine platforms to achieve further efficiency and emission-reduction gains.

INTRODUCTION

Under both stoichiometric and lean-fueling conditions, internal and external EGR can significantly reduce NO_x emissions and increase fuel efficiency in spark-ignition (SI) engines. One specific reason for current interest in high EGR is because of its role in promoting homogeneous charge compression ignition (HCCI) and other high-efficiency, clean combustion (HECC) modes. Unfortunately, higher levels of EGR also promote combustion instability because of the nonlinear feedback from prior cycles. Under lean fueling conditions, these instabilities appear as misfire or partial burn events. Under other conditions, the combustion can alternate between propagating flame and homogeneous ignition. In either of these cases, combustion events can occur in a regular or complex pattern of alternating cycles of good and poor combustion quality, depending on the strength of the feedback and the sensitivity of combustion to small changes in the initial conditions at the beginning of each cycle.

EGR is a key source of feedback because any gas reintroduced into the cylinder contains any combustion products or unburned fuel or air that might remain from preceding cycles. The final temperature from previous combustion events also influences the starting temperature of succeeding events. When ignition and flame propagation become extremely sensitive to small changes in these initial conditions, large cycle-to-cycle variability can occur, resulting in increased emissions of unburned fuel (during partial burns and misfires) and NO_x (produced during the succeeding enhanced-combustion events). **Figure 1** illustrates an example of the correlation observed between combustion variability and NO_x emissions for cycle-resolved experimental engine measurements. Obviously, such cyclic variability can negate the desired benefits of dilute operation and puts a practical limit on the amount of dilution that can be achieved.

We have developed a hybrid engine model by incorporating a detailed two-zone combustion model into commercially available engine-modeling software – specifically, WAVE from Ricardo, Inc. – that is capable of predicting the development of combustion instabilities in SI engines during dilute, high-EGR operation. The behavior of specific engine platforms (including large, reciprocating, natural gas engines) can be simulated by careful calibration of the two-zone model and accurate modeling of the engine and manifold geometry in WAVE. For the current study, the model is used to simulate the behavior of a single-cylinder, 0.611-L gasoline-powered Waukesha CFR research engine and estimate the additional gains in fuel efficiency and emissions reductions

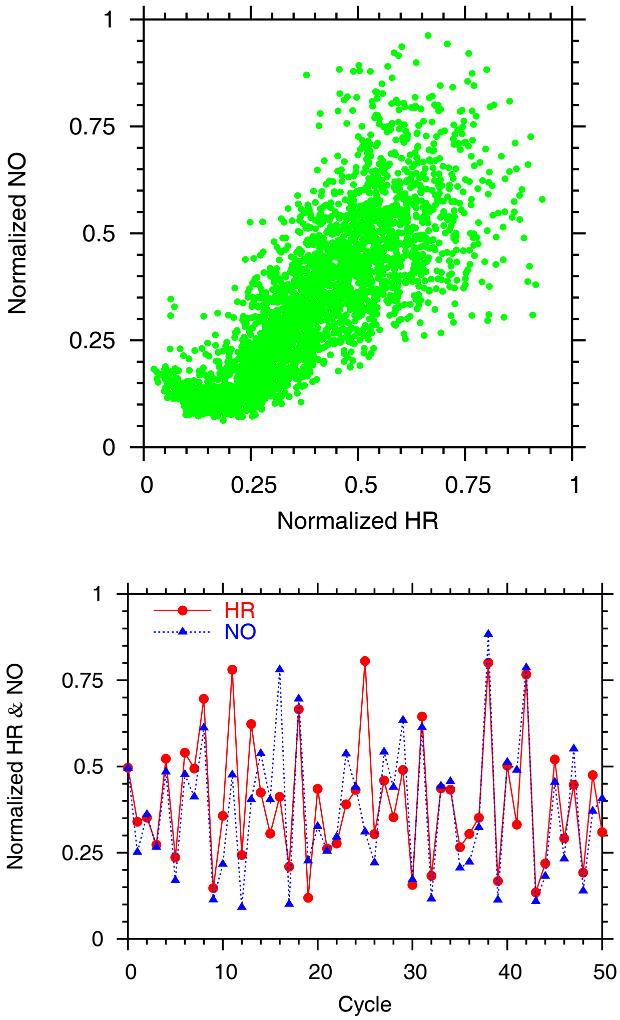


Figure 1 Cycle-resolved NO measurements from a Kohler natural gas gen-set operating at lean fueling conditions confirm the correlation between high heat-release combustion events and high production of NO.

which may be gained through the application of adaptive feedback control.

DESCRIPTION OF THE HYBRID MODEL

The primary component of the hybrid model is a WAVE engine-simulation code which can be used to model a specific SI engine geometry. To simulate SI combustion, Ricardo, Inc.'s commercial WAVE engine modeling software uses a simple Wiebe function with no method of self-correction to account for the effects cycle-resolved changes in equivalence ratio and reactant temperature have on combustion performance. Therefore, in the hybrid model, results from a two-zone combustion model are used to provide feedback to WAVE through a Simulink interface to modify the properties of the SI Wiebe function to correct for these effects. The use of a more accurate and detailed combustion model that accounts for temperature effects and retains the physics of flame propagation and the ability to incorporate physical characteristics and flow dynamics of the engine through WAVE provides the hybrid model with distinct advantages over the simple model used in our previous studies **[1,2]**.

Two-zone Model

Specific details of the two-zone model are given by **[3,4]**. The model combines thermodynamic constraints defined by Caton **[5,6]** with a turbulent combustion model developed by Tabaczynski *et al.* **[7,8]** and described by Stone **[9]**. We also use the laminar flame speed correlations developed by Metghalchi and Keck **[10]**, and described by Turns **[11]** and Stone **[9]**.

An important aspect of our model is that we constrain the overall combustion process to be consistent with the global thermodynamics. The contents of the cylinder are assumed to be a closed system and model the behavior during the portion of the cycle that the valves are closed. Combustion is assumed to be quenched as soon as the exhaust valve opens.

Each zone is considered to be homogeneous. The composition of the unburned zone is frozen, while the burned zone is frozen for temperatures below 1600 K and assumed to be at equilibrium for temperatures above 1600 K. Rather than performing complex chemical equilibrium calculations and determining mixture properties online, we use look-up tables generated offline to relate internal energy, temperature, pressure, and composition. Components of the unburned zone are fresh intake charge and residual gas from the previous cycle. By computing the total number of moles of unburned fuel, oxygen and combustion products in these components, an effective equivalence ratio and residual fraction are computed.

In the present model, the temperature of the unburned mixture and the pressure at the start of each cycle simulation are specified rather than modeling valve flow and heat loss of the residual gas. The two-zone model can be ran for a range of initial conditions (*e.g.*, temperature, pressure, and effective equivalence ratio) to produce a look-up table supplying the burned fraction of fuel as a function of the initial conditions or it can be used as a called subroutine in WAVE to simulate the combustion process while the valves are closed.

For further details on the two-zone model, the reader is referred to **[3,4]**.

Integrated WAVE Model

For the current investigation, the WAVE model was designed to simulate the behavior of a single-cylinder, 0.611-L Waukesha CFR research engine with normal and higher than normal EGR. The single SI cylinder is modeled using WAVE's IRIS advanced cylinder model with port fuel injection. The geometry and valve-lift profiles of the CFR engine were measured and used to construct the model. Standard values for discharge and swirl coefficients are used to approximate those values in lieu of experimentally determining the actual values. This may introduce a small amount of error to the simulations but it was not critical to the main objectives here. The intake and exhaust manifolds are represented by straight pipes connected to an appropriate ambient source or sink. Throughout the current study, intake ambient conditions were set to 300 K and 0.9 bar to account for throttling in the engine (the throttle is not included in the WAVE model) and the exhaust ambient was set to 300 K and a back pressure of 1.1 bar.

A Simulink interface is used to provide cycle-resolved feedback to the WAVE simulation which is being evaluated at a time resolution that is typically better than crank-angle resolved. After each time step, the WAVE simulation provides information to the Simulink interface that is needed to calculate heat release and determine appropriate feedback corrections.

Information from the two-zone model regarding the effect of initial conditions on combustion performance is included in a look-up table within the Simulink code. Each cycle, once the intake valve has closed in the WAVE simulation, the Simulink interface uses the initial conditions of the trapped gas provided by WAVE in conjunction with the look-up table of data from the two-zone model to determine the mass fraction of fuel that will be burned during the current cycle. This information is then fed back into the WAVE simulation on the succeeding time step. Additional modifications to the Wiebe function can be made in the same manner and we hope to further refine the combustion behavior in future studies.

It should be noted that, as an alternative to this approach, it is possible to completely replace the SI Wiebe function in the WAVE simulation with the two-zone model as a called subroutine with WAVE supplying the initial conditions based upon its valve flow and heat transfer models. While doing so should increase the accuracy of the simulation, the required calculation time is increased by several orders of magnitude. The current approach is thus a compromise to allow relatively rapid simulation of several thousand successive cycles.

Adaptive Feedback Control

Cycle-resolved adaptive feedback control can also be simulated using the Simulink interface. The objective of such control is to reduce the severity of the cycle-to-cycle variation and extend the practical operating range of the engine. In this investigation, a map-based prediction strategy **[12,13]** is used to predict the combustion performance one cycle in advance. The map-based strategy works by observing several hundred cycles of uncontrolled behavior at a given operating condition and using least-squares regression to develop a relationship, or map, between the heat release of the current cycle and that of the following cycle. Once the map is obtained, the controller determines the heat release from the current cycle and uses it in conjunction with the map to predict the behavior of the following cycle. A control perturbation proportional to the difference between the predicted behavior and a desired target point is then applied to the following cycle to steer the system toward the desired behavior. Such control is proactive to prevent expected deviations in behavior rather than reactive to correct for deviations which have already occurred. In the current study, control perturbations were applied to the fueling of the subsequent cycle unless otherwise specified.

VALIDATION OF THE HYBRID MODEL

We chose to model the Waukesha CFR gasoline engine because of our familiarity with the platform and the availability of data from this engine that exhibits extreme cyclic variability at lean conditions and different levels of EGR **[14]**. The hybrid model was programmed to match the geometry of the CFR engine and the operating conditions at which the data was collected.

In the CFR engine experiments, internal EGR occurred due to trapping of residual gas and exhaust backflow because of valve overlap. The nominal trapped residual fraction was further increased for some experiments by applying direct back pressure on the tailpipe. The combustion instability and cyclic variability were clearly more severe at the higher EGR levels **[14,15]**. The character of the combustion oscillations also became more deterministic and complex, as would be expected for a highly nonlinear feedback process.

To simulate the CFR experiments, adjustments were made to the WAVE input parameters (specifically the exhaust valve closure timing (EVC)) to produce varying levels of internal EGR, including those estimated for the engine experiments. As shown in **Figure 2**, with EVC at 360°ATDC (as set on the CFR engine), the hybrid model predicts an asymptotic decrease in heat release with equivalence ratio. However, with only a slight advancement of EVC (to 351°ATDC), the instabilities begin to develop resulting in a clear bifurcation and period-2 behavior characterized by alternating cycles of partial burn and enhanced combustion with only 6% internal EGR (by mass). With further advancement of EVC, period-2 behavior oscillations become larger and alternating misfires more severe. Power output also begins to drop significantly. Once the internal EGR reaches 30-40% (EVC prior to 315°ATDC), the lower limit of equivalence ratio at which the engine model completely dies begins to increase.

It is believed that further refinement of the two-zone combustion model and more precise matching of the engine geometry will result in better comparisons to the CFR engine data. Specifically, we know from the experiments that the nonlinear sensitivity of the combustion to small changes in residual composition and temperature was actually greater than that predicted by the current two-zone model. This greater sensitivity in turn caused more complicated oscillatory behavior at sufficiently lean conditions. However, it is already clear that, with proper accounting of the residual fraction, the current simple model is capable of predicting the development of the basic combustion instabilities observed in the CFR engine.

Figures 3 and **4** provide additional comparisons of predicted trends for the hybrid model and CFR engine data at the various EGR levels. **Figure 3** depicts bifurcation diagrams for the engine and model showing the development of combustion instabilities (as reflected in the integrated heat release) and period-2 behavior as the as-fed equivalence ratio decreases (and thus the sensitivity of the combustion to feedback increases). The engine data shown in **Figure 3a)** illustrate the effect of stochastic perturbations (noise) on combustion parameters, which smear the underlying deterministic behavior; however, the dense concentration of points forming darker bands along the top and bottom of the plot reveal the underlying period-2 oscillation. Indeed, once the data is filtered with a fitting technique and the stochastic perturbations are removed (**Figure 3b)**), the period-2 behavior is clearly evident **[16]**.

In **Figure 3c)**, we show a bifurcation diagram for the hybrid model where a small amount of Gaussian noise (σ^2 = ±0.15%) has been added to the nominal amount of fuel injected into the cylinder during each cycle. The predicted behavior closely matches that observed in the CFR engine. With the noise removed (**Figure 3d)**), the unique signature of period-2 behavior can clearly be observed, demonstrating that the hybrid model is able to predict combustion instabilities arising from deterministic processes. This underlying instability is

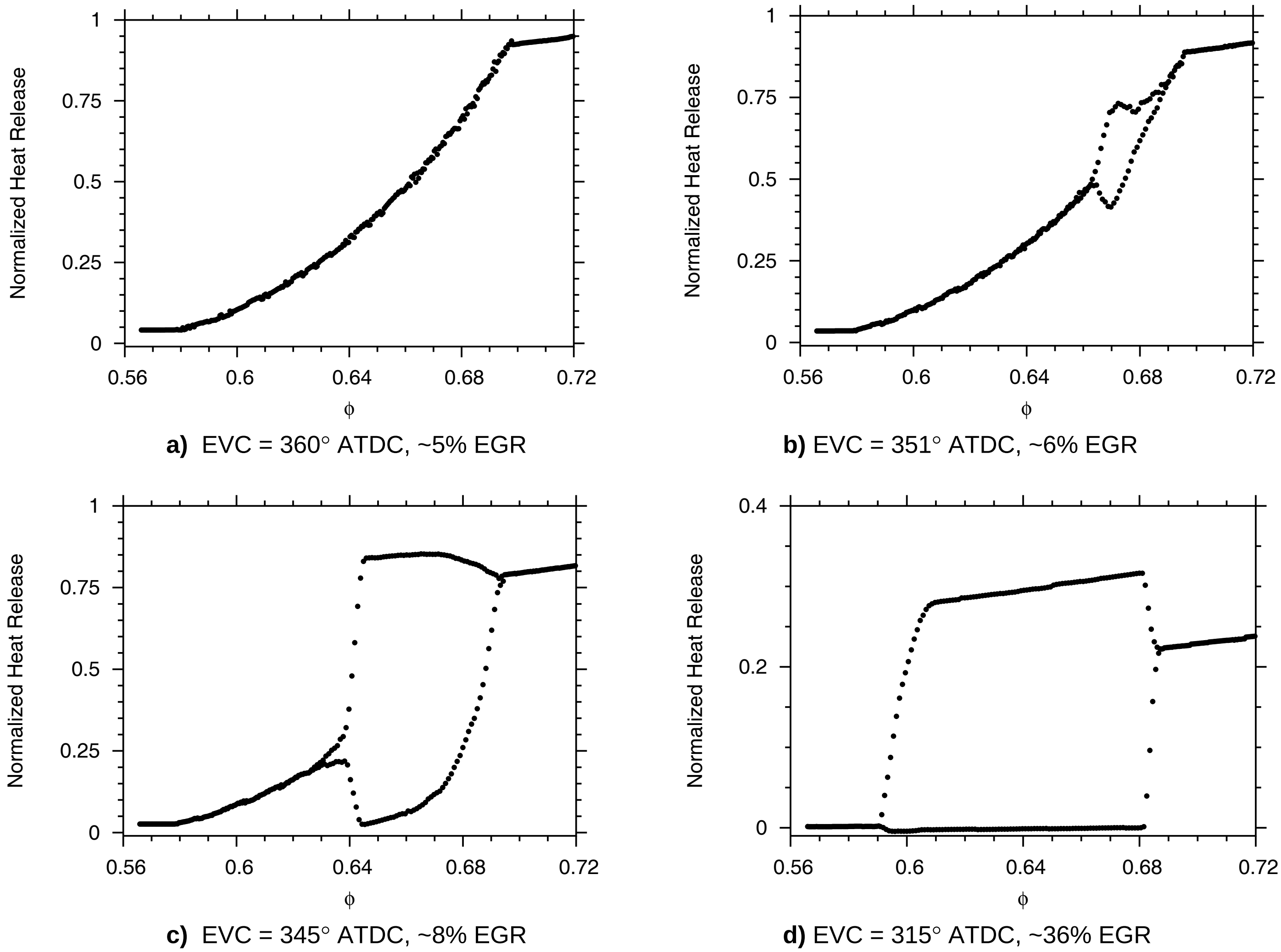


Figure 2 Increasing the internal EGR by advancing the timing of the exhaust valve closure (EVC) promotes the development of combustion instabilities and period-2 heat-release oscillations in the hybrid model.

amplified by random perturbations in parameters such as equivalence ratio and is evident in the CFR engine data.

Figure 4 illustrates the same bifurcation trends as in **Figure 3**, except for a higher internal EGR level. One shortcoming of the hybrid model appears to be that the complex nature of the combustion oscillations at very lean conditions is not fully captured. We conjecture that this is primarily due to deficiencies in the current two-zone combustion model. Specifically, it appears that the two-zone model does not correctly predict the rapid drop in flame speed that actually occurs at very lean conditions. This type of inaccuracy would explain why (as shown in **Figure 3**) the model under predicts the equivalence ratios at which both combustion bifurcations first begin and also when total flameout occurs.

APPLICATION OF ADAPTIVE FEEDBACK CONTROL

By applying adaptive feedback control to the hybrid model, it is possible to greatly reduce the severity of the cycle-to-cycle fluctuations in performance and emission levels of NO and unburned hydrocarbons (UHC) observed at dilute conditions. **Figure 5** presents time series plots of heat release and NO and UHC emissions predicted by the hybrid model (using the standard models supplied with WAVE by Ricardo, Inc.) for a particular dilute operating condition. In this example, after observing 500 cycles of uncontrolled behavior while in "learning mode", the map-based adaptive controller begins to apply control perturbations to the fuel-air ratio of the fresh charge injected each cycle.

Without adaptive control, the model prefers to operate in the typical period-2 pattern with alternating cycles of partial burn and enhanced combustion. Intermittently, the stochastic perturbations applied to the fueling cause the model to visit the region around the unstable fixed point where it briefly becomes entrained (*e.g.*, during the period roughly between cycles 200 and 250 in **Figure 5**). The intention of adaptive control is to stabilize the region around this fixed point making it easier to entrain the behavior and proactively predict and prevent wanderings from the fixed point which lead to the more extreme combustion behaviors. Because the period-1 fixed point lies on the system map for the given operating condition,

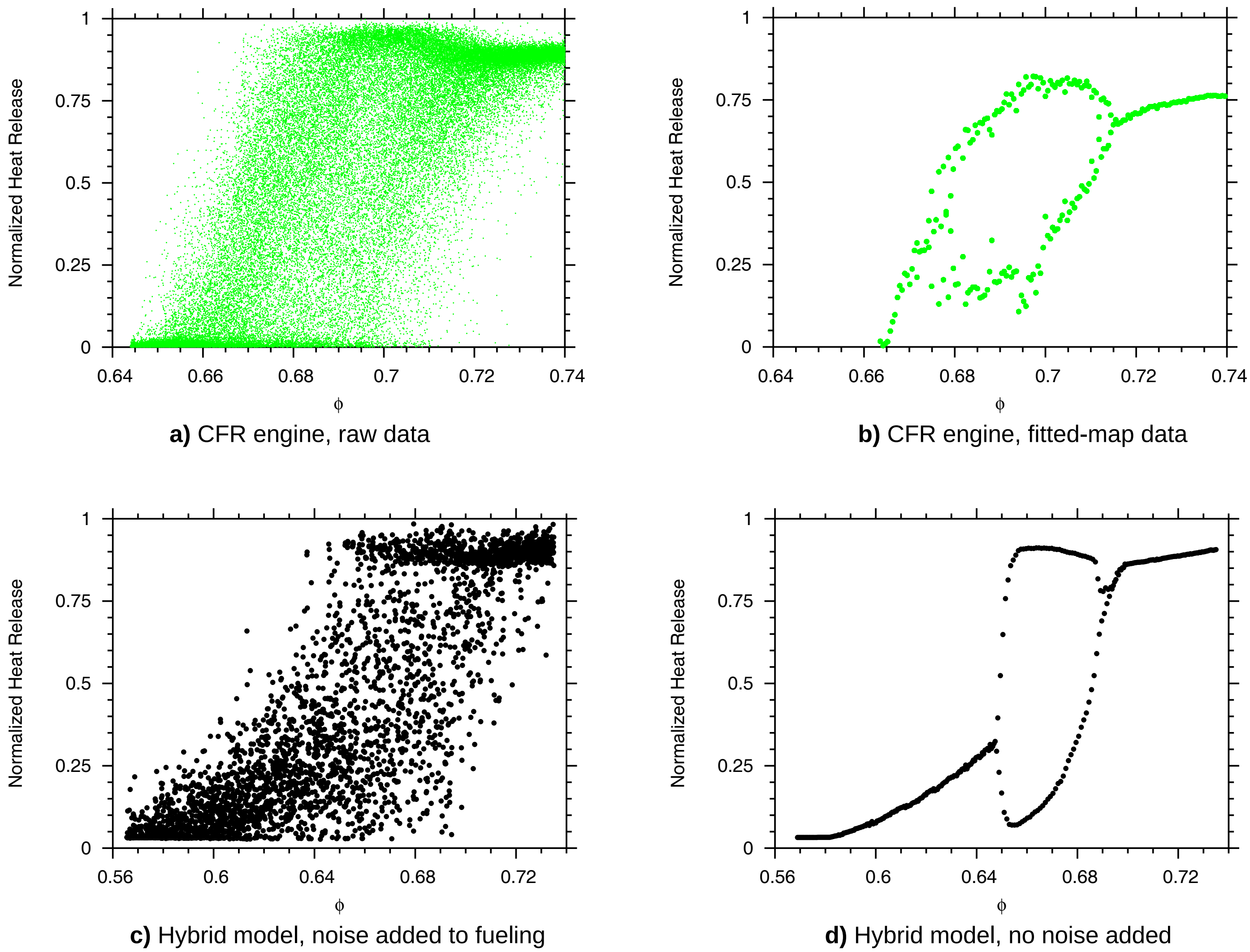
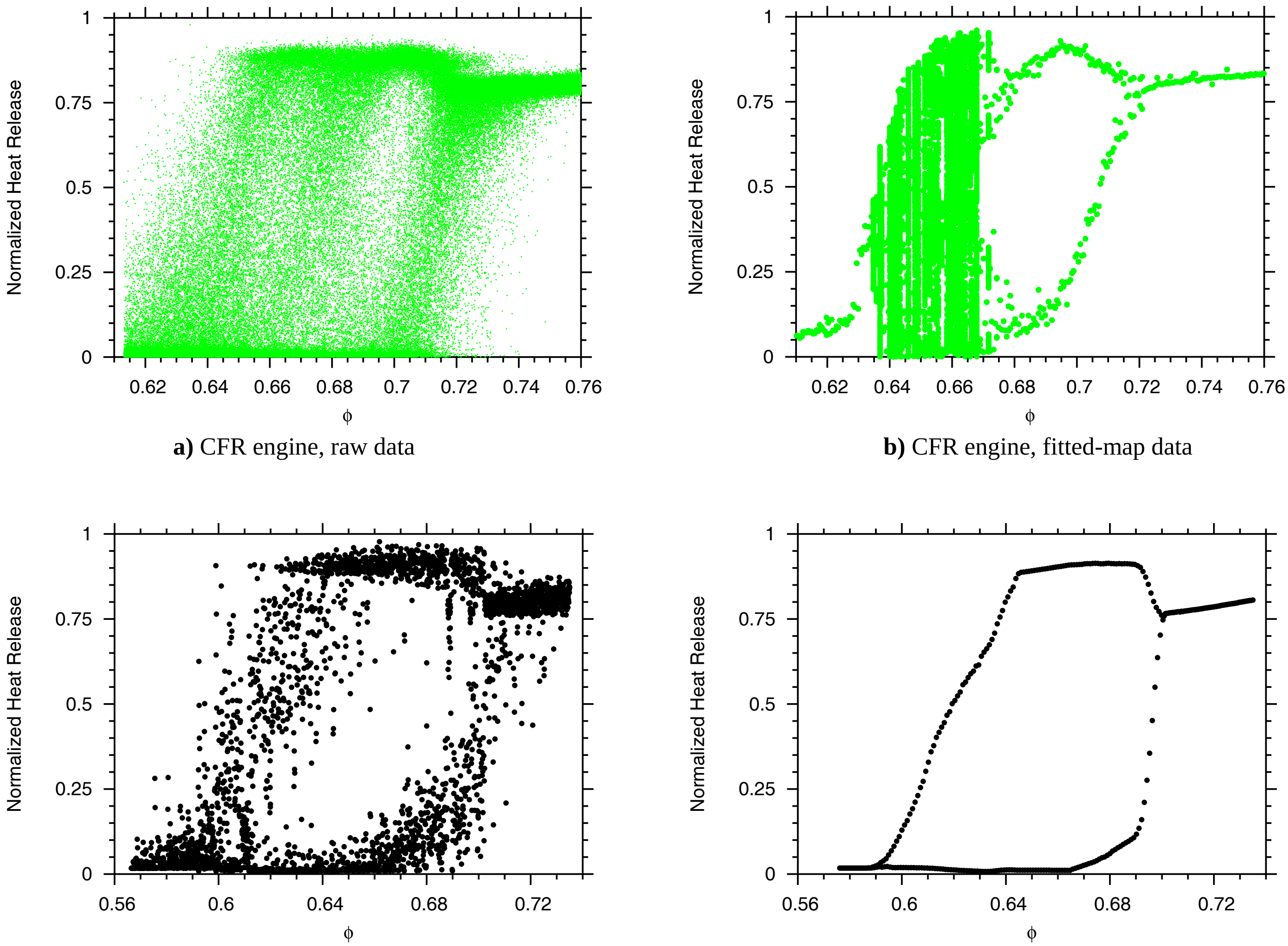


Figure 3 Bifurcation plots for the CFR engine and hybrid model showing the development of combustion instabilities and period-2 behavior as equivalence ratio decreases for nominal internal EGR.

targeting this fixed point allows control to be achieved with no net fuel penalty due to the fueling control perturbations **[12,13]**. Targeting points which do not lie on the system map is possible but results in a net increase or decrease in fuel consumption. For the example shown in **Figure 5**, the average fuel consumption (black lines) actually decreases slightly with active control suggesting that the controller has slightly under-estimated the system map and location of the period-1 fixed point.

With active control, the variability in predicted emission levels of NO and UHC is reduced considerably; however, there is little change in the time-averaged emission levels. This should be expected as we are targeting the unstable, period-1 fixed point which lies roughly at the center of the period-2 fixed points that correspond to partial burn (high UHC, low NO_x) and enhance-combustion recovery (low UHC, high NO_x). The controller acts to keep the behavior entrained near the period-1 fixed point; thus, the controlled behavior is very similar to what we see when the system becomes briefly entrained at this point without control (*e.g.*, during the period roughly between cycles 200 and 250 in **Figure 5**). Application of control in this manner is meant to smooth operating performance at a particular equivalence ratio so that it becomes more practical to operate at higher dilution levels to achieve additional efficiency gains and emissions reductions rather than improving average efficiency and emissions at that condition.

In **Figure 6**, control is achieved in the model by varying the timing of the exhaust valve closure to increase or decrease the percentage of internal EGR retained during the following cycle. Results are similar to those achieved by varying fueling. However, this method allows for greater latitude in selecting a target point without incurring a fuel penalty. With slight modifications to the control algorithm and by perturbing fueling, we have achieved increased stability by targeting the upper period-2 fixed point. However, the associated fuel penalty was too large for this technique to be practical. In the future we hope to successfully demonstrate this technique using the exhaust-valve timing control approach.



a) CFR engine, raw data

b) CFR engine, fitted-map data

c) Hybrid model, noise added to fueling

d) Hybrid model, no noise added

Figure 4 Bifurcation plots for the CFR engine and hybrid model showing the development of combustion instabilities and period-2 behavior as equivalence ratio decreases for higher level of internal EGR.

CONCLUSIONS AND FUTURE WORK

Overall, while there are some discrepancies in prediction details compared to the experimental CFR engine data, the hybrid model accurately captures the general trend of development of combustion instabilities and the onset of period-2 bifurcations in heat release with increasing EGR. We expect that further refinement of the two-zone combustion submodel and improvement of geometric details in the WAVE parameters will further improve the overall prediction accuracy.

Previous studies **[13]** have demonstrated similar dynamic trends in dilute combustion behavior for a wide variety of SI engines operating on various fuels, including natural gas. Thus, we expect that the hybrid model described here will be capable of accurately simulating the dilute combustion behavior of large, reciprocating, natural gas engines as long as proper calibration and geometric details are included. The hybrid-model approach offers distinct advantages for integrated systems and controls studies because it combines both the essential physics of combustion instability and the flexibility of the WAVE software to account for the effects numerous engine design parameters in an interactive fashion. We fully expect that this type of model can be adapted to simulate observed combustion dynamics, develop and test control strategies for high EGR operation, and even to predict the impact of design changes on engine performance under high EGR conditions for a range of engine platforms.

Although combustion instability in this study was restricted to lean fueling conditions, the nonlinear effect of EGR can also affect other critical operating transitions. For example, high EGR is commonly used to promote HCCI. In future publications, we will demonstrate how the instabilities associated with the transition from conventional to HCCI combustion have similarities to lean fueling instabilities. We expect that our hybrid-model approach will also be useful in this context as well.

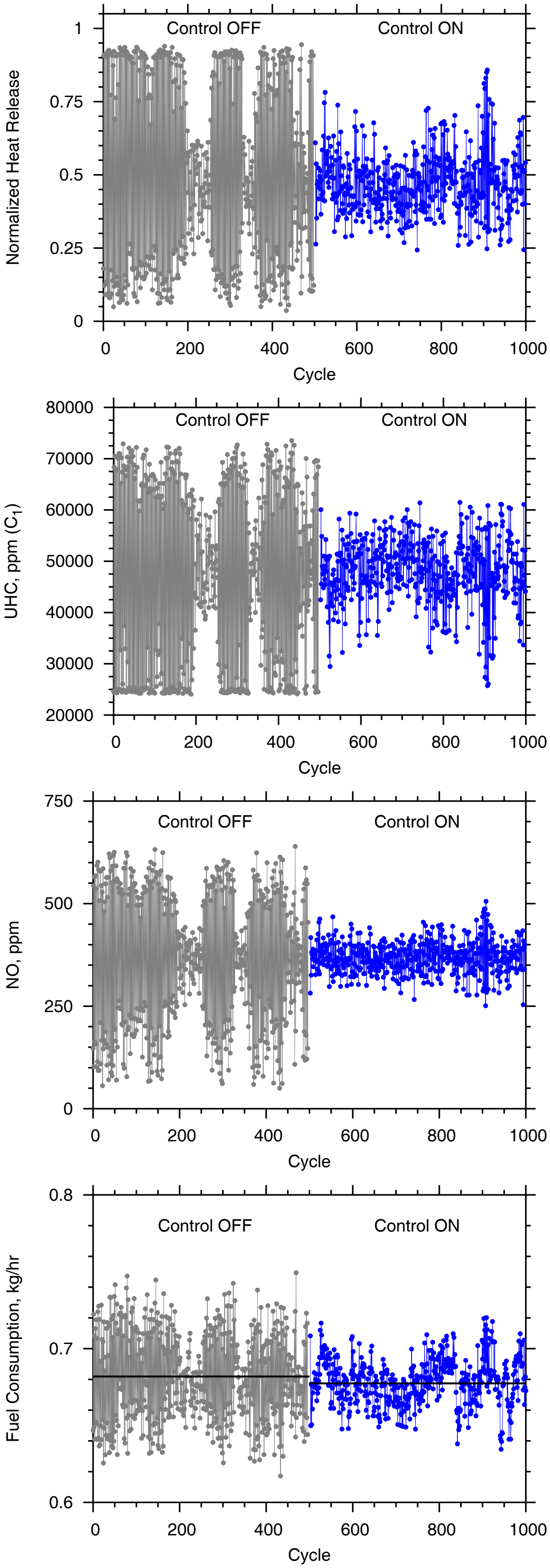


Figure 5 An example of the reductions in cyclic variation in the performance and emission levels of the hybrid model obtained through the application of adaptive feedback control with perturbations to the fueling of each cycle.

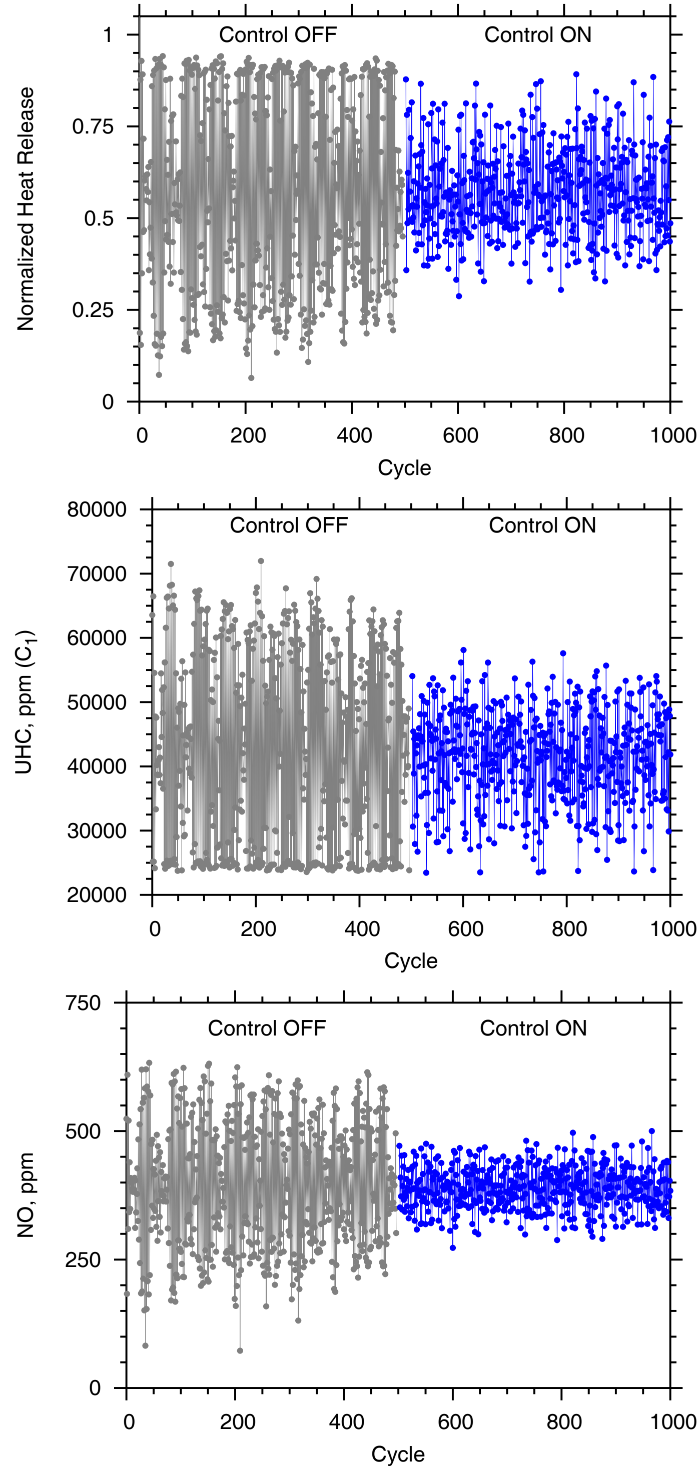


Figure 6 An example of the reductions in cyclic variation in the performance and emission levels of the hybrid model obtained through the application of adaptive feedback control with perturbations to the timing of the exhaust valve closure (EVC).

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REFERENCES

1. Daw CS, Finney CEA, Green JB, Jr., Kennel MB, Thomas JF, Connolly FT (1996) "A simple model for cyclic variations in a spark-ignition engine." SAE 962086.
2. Daw CS, Kennel MB, Finney CEA, Connolly FT (1998) "Observing and modeling nonlinear dynamics in an internal combustion engine." *Physical Review E*; **57**(3), 2811-2819.
3. Chakravarthy K, Wagner RM, Daw CS (2005) "On the use of thermodynamic modeling for predicting cycle-to-cycle variations in a SI engine under lean conditions." SAE 05FFL-203.
4. Chakravarthy K, Daw CS, Wagner RM, Kaul BC, Drallmeier JA, Sarangapani J (2005) "Modeling nonlinear dynamics in a spark ignition engine with a two-zone thermodynamic model." *Proceedings of the 4th Joint Meeting of the U.S. Sections of the Combustion Institute*.
5. Caton JA (2000). "A review of investigations using the second law of thermodynamics to study internal-combustion engines." SAE 2000-01-1081.
6. Caton JA (2002). "A cycle simulation including the second law of thermodynamics for a spark-ignition engine: implications of the use of multiple-zones for combustion." SAE 2002-01-0007.
7. Tabaczynski RJ, Ferguson CR, Radhakrishnan K (1977) "A turbulent entrainment model for spark-ignition engine combustion." SAE 770647.
8. Tabaczynski RJ, Trinker FH, Shannon BAS (1980) "Further refinement and validation of a turbulent flame propagation model for spark ignition engines." *Combustion and Flame*; **39**, 111-121.
9. Stone R (1999) *Introduction to Internal Combustion Engines*. SAE.
10. Metghalchi M, Keck JC (1982) "Burning velocities of air with methanol, iso-octane, and indolene at high pressure and temperature." *Combustion and Flame*; **48**, 191-210.
11. Turns SR (2000) *An Introduction to Combustion*. McGraw-Hill.
12. Edwards KD, Wagner RM, Daw CS (2004) "Adaptive control to limit cyclic dispersion in a lean spark-ignition combustion model during fueling transients." SAE 2004-01-0895.
13. Edwards KD, Wagner RM (2004) "Application of adaptive control to reduce cyclic dispersion near the lean limit in a small-scale, natural gas engine." Paper ICEF2004-855. ASME Internal Combustion Engine Division 2004 Fall Technical Conference; 24-27 October 2004, Long Beach, CA, USA.
14. Wagner RM, Drallmeier JA, Daw CS (2000) "Characterization of lean combustion instability in premixed charge spark ignition engines." International Journal of Engine Research; **4**:1, 301-320.
15. Wagner RM (1999) *Identification and Characterization of Complex Dynamic Structures in Spark-ignition Engines*. Ph.D. dissertation. University of Missouri-Rolla.
16. Wagner RM, Daw CS, Green JB, Jr. (2001) "Low-Order Map Approximations of Lean Cyclic Dispersion in Premixed Spark Ignition Engines." SAE 2001-01-3559.