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CRADA Final Report (ORNL-Ford Motor Company, 1995)
CRADA Agreement Number ORNL95-0337

Engine Control Improvement Through Application of Chaotic Time Series Analysis

A Final Report submitted to the
Office of Energy Efficiency and Renewable Energy, Department of Energy,
July 2003

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Abstract

The objective of this program was to investigate cyclic variations in spark-ignition (SI) engines under lean fueling conditions and to develop options to reduce emissions of nitrogen oxides (NOx) and particulate matter (PM) in compression-ignition direct-injection (CIDI) engines at high exhaust gas recirculation (EGR) rates. The CIDI activity builds upon an earlier collaboration between ORNL and Ford examining combustion instabilities in SI engines. Under the original CRADA, the principal objective was to understand the fundamental causes of combustion instability in spark-ignition engines operating with lean fueling. The results of this earlier activity demonstrated that such combustion instabilities are dominated by the effects of residual gas remaining in each cylinder from one cycle to the next. A very simple, low-order model was developed that explained the observed combustion instability as a noisy nonlinear dynamical process. The model concept lead to development of a real-time control strategy that could be employed to significantly reduce cyclic variations in real engines using existing sensors and engine control systems. This collaboration led to the issuance of a joint patent for spark-ignition engine control.

After a few years, the CRADA was modified to focus more on EGR and CIDI engines. The modified CRADA examined relationships between EGR, combustion, and emissions in CIDI engines. Information from CIDI engine experiments, data analysis, and modeling were employed to identify and characterize new combustion regimes where it is possible to simultaneously achieve significant reductions in NOx and PM emissions. These results were also used to develop an on-line combustion diagnostic (virtual sensor) to make cycle-resolved combustion quality assessments for active feedback control. Extensive experiments on engines at Ford and ORNL led to the development of the virtual sensor concept that may be able to detect simultaneous reductions in NOx and PM emissions under low temperature combustion (LTC) regimes. An invention disclosure was submitted to ORNL for the virtual sensor under the CRADA.

Industrial in-kind support was available throughout the project period. Review of the research results were carried out on a regular basis (annual reports and meetings) followed by suggestions for improvement in ongoing work and direction for future work. A significant portion of the industrial support was in the form of experimentation, data analysis, data exchange, and technical consultation. An ORNL researcher also spent a year as a visiting researcher at Ford Motor Company under the CRADA.

1. Statement of Objectives

The following goals were pursued in this project:

1. Reduce cyclic combustion variations in spark-ignited engines under idle conditions.
2. Reduce CIDI engine-out NOx emissions by 50% or more with a minimal penalty for PM emissions.
3. Lower the performance requirements for post-combustion emissions controls for CIDI engines.

2. Benefits to the Funding DOE Office's Mission

Due to the increasing number of light-duty trucks and sport utility vehicles consuming petroleum in the United States, there is a need to increase the energy efficiency of all vehicles and enable the use of the most efficient power plant (CDI engines) in light-duty trucks and sport utility vehicles. This will aid in reducing the United States dependence on foreign oil. This directly supports the Office of Energy Efficiency and Renewable Energy's top priority. The objectives of this CRADA directly contribute to the effort to reduce foreign petroleum consumption by striving to improve the energy efficiency of spark-ignited passenger vehicles and by enabling a larger market penetration of diesel engines in the U.S. market.

3. Technical Discussion of Work Performed by All Parties

In one phase of this collaborative effort, researchers from Ford and ORNL demonstrated a control approach for reducing cycle-to-cycle variations in an internal combustion engine incorporating a number of unique features. We believe that these results are the first successful demonstration of control of cycle-to-cycle combustion variations on a production vehicle.

A simple spark-ignition engine model was developed that mimics the behavior of an internal combustion engine under lean fueling. The model identifies the coupling between cycles via residual gases remaining in the cylinder after a combustion event, which allows us to exploit the deterministic nonlinear instability inherent in cyclic combustion variations. Unlike previous investigators, we recognized that the dominant combustion instability arises from nonlinear bifurcations near the lean limit. This information is employed to recognize when the instability begins and how it can be countered with feedback perturbations.

The contribution of stochastic perturbations were also incorporated in the simple spark-ignition engine model. The observed combustion instabilities result from the combined effects of stochastic perturbations and nonlinear determinism, which can be classified as a noisy nonlinear dynamics. While the basic deterministic structure is not destroyed by the high-dimensional engine parameter perturbations (e.g., fluctuations in the fuel injector), these perturbations do modify the instabilities and the region of air/fuel ratios where they occur. Engine design or operating changes that impact the parameter fluctuations can thus affect cyclic combustion variations.

Even though the combustion variations result from a complex noisy nonlinear dynamic process, simple cycle resolved feedback perturbations can be used to reduce the cyclic combustion variations. Since our approach allows us to identify the deterministic component in combustion variations at lean conditions, we are able to reduce the instability with explicit and simple real-time control algorithms. Computational complexity and overhead are thus minimized. The nonlinear sensitivity of the combustion to small changes in parameters such as fuel injection pulse width and spark timing allows effective control with very small control inputs. This makes it possible to improve engine operation with little or no net change to time average parameter values.

The implementation of this control approach has been demonstrated in a commercial automobile using currently available sensors and control systems. Application of this approach using crankshaft acceleration as a measure of torque and fuel pulse width modification as a control, showed as much as a 30% reduction in root mean square variation near the lean limit. By using torsional acceleration as the measured dynamic variable, we were able to detect the dominant combustion patterns despite the complex transformations imposed by the crankshaft and its dynamics. Furthermore, the control algorithms were adapted for implementation in a production vehicle using its existing electronic engine control (EEC) computer.

The control algorithm has also been implemented simultaneously on multiple cylinders. Our feedback control algorithm was adapted to successfully deal with fuel spillover effects from cylinder-to-cylinder and phasing interactions between cylinders. Without this refinement, control of commercial multi-cylinder engines would not be feasible.

In the second phase of the CRADA, our focus shifted to using "smart" EGR control to reduce NOx and PM emissions in CIDI engines. Information from CIDI engine experiments, data analysis, and modeling are being employed to develop an on-line combustion diagnostic (virtual sensor) to make cycle-resolved combustion quality assessments for active feedback control during operation low temperature combustion regimes. Analysis and modeling of experimental data from ORNL and Ford Motor Company have led to the development of concept for an on-line combustion diagnostic for active feedback control. This diagnostic index would be calculated for each cycle.

Actual EGR utilization in production engines is typically less than optimal because of high HC and PM emissions under high EGR conditions. Until recently, it was believed that PM continues to increase with increasing EGR rate. ORNL has identified two operating strategies which yield simultaneous reductions in NOx and PM emissions. ORNL was able to operate an engine in these combustion regimes under high EGR conditions with air-fuel ratios lean of stoichiometric. Extensive experiments were performed in these regimes to improve the understanding of the combustion process and for exploring strategies for reducing the fuel penalty associated with operation in these regimes. The information gathered during these ongoing experiments was also used in the development of diagnostic tools (virtual sensor) for characterizing combustion quality on a cycle-by-cycle basis to provide active, real-time feedback for predictive control. This type of control will probably be necessary for effective operation in these low temperature combustion regimes.

The combustion diagnostic is derived from in-cylinder pressure measurements that detect correlations between late-stage combustion and emissions, it can be used to detect unacceptable levels of PM emissions at high EGR levels and possibly detect operation in a low temperature combustion regime. The combustion metric is used to calculate the heat release rate profile for each combustion event of every cylinder. The heat release rate profile is then sent to an algorithm that determines the transition point between premixed combustion and diffusion combustion and calculates the ratio of diffusion combustion to premixed combustion. The ratio of diffusion combustion to premixed combustion can be employed to develop correlations between the combustion metric emissions (i.e., one range of values correlates with standard combustion and another range of values correlates with low temperature combusiton). This information can then be used as an on-line diagnostic for EGR utilization and fuel injection parameters. More specifically, it can serve as a platform for detection of incipient emissions spikes associated with entering and leaving targeted combustion regimes and initiate the counteracting feedback (e.g., fuel injection modulation). The combustion diagnostic can also be used to determine cylinder-to-cylinder imbalances in EGR distribution during engine operation.

Further details regarding the activities performed under the CRADA can be found in the provided references.

4. Subject Inventions

This collaboration has lead to the first successful demonstration of chaos control in engines and has led to a patent. The patent was issued in 1999 under:

"Method of Controlling Cyclic Variation in Engine Combustion," L. I. Davis, Jr., C.S. Daw, L. A. Feldkamp, J. W. Hoard, F. Yuan, and F. T. Connolly. U.S. Patent No. 5,921,221 (1999).

An invention disclosure was submitted for the virtual sensor concept. UT-Battelle elected title to the invention on May 21, 2002. The invention disclosure was submitted as:

1089C/S-99,267 "A Combustion Diagnostic for Active Engine Feedback Control," J. B. Green Jr., R. M. Wagner, and C. Stuart Daw.

For more information about the status on this invention disclosure please contact Larry Dickens at (865) 576-9682.

5. Commercialization Possibilities

Commercialization of the lean spark-ignition chaos control strategy could be achieved today. Ford Motor Company has demonstrated that the control strategy can be employed on a production vehicle and could make widespread use of the strategy if they felt a suitable business case existed. Commercialization of the virtual sensor could be feasible in the near future if diesel engine manufacturers are able to make wide spread use of low temperature combustion regimes and mixed mode engine operation using pressure transducers for feedback control. Approximately 5-10 years of further research may required for the previously mentioned scenario to become a reality. Therefore, the commercialization of this technology is at least five years away.

6. Plans for Future Collaboration

ORNL and Ford are continuing informal collaborations in the areas of combustion and aftertreatment. A new CRADA the area of lean NOx aftertreatment is being discussed with Ford. In this effort, regeneration strategies and the overall performance of lean NOx traps would be investigated.

7. Conclusions

Our engine application of chaos theory has been done in collaboration with Ford Motor Company. This collaboration has lead to the first successful demonstration of chaos control in engines and has led to a patent. The initial research focus was on gasoline spark-ignition engines, but this work was extended to compression-ignition engines (diesel engines) as well.

The specific condition where our engine control methodology applies is when the engine is operating very fuel lean or when the engine is operating at high exhaust gas recirculation level in low temperature combustion regimes. In both of these cases, combustion quality changes as the excess air or exhaust gas dilutes the combustion mixture. The developing combustion instabilities are exhibited as incomplete or unusually energetic combustion events, which exacerbate unwanted emissions and degrade fuel economy. We have demonstrated that, using information from existing engine sensors, it is possible to detect and analyze the combustion instabilities when they occur. By using the engine control computer to detect and analyze these instabilities very quickly, it is possible to forecast future bad combustion events with a relatively high accuracy and make rapid engine adjustments to prevent these bad events before they ever happen. Based on this knowledge, real-time, high-speed interactive chaos control of the engine in a commercial spark-ignited passenger vehicle has been demonstrated. The virtual sensor concept has also shown promise as a combustion diagnostic for diesel engine operation in low temperature combustion regimes. The combination of operating in new combustion regimes in conjunction with more advanced control is expected to lower the performance requirements of post-combustion emission control devices.

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