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Application of nonlinear feedback control to enhance the performance of a pulsed combustor

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Abstract

A feedback control strategy is applied to enhance the performance of a laboratory-scale pulsed combustor operating near the lower flammability limit. As with many combustion processes, at lean conditions, combustion instabilities develop which result in complex, low-frequency fluctuations in fuel concentration and lead directly to misfire and flameout. The control strategy exploits the highly nonlinear relationship between equivalence ratio and reaction rate at lean operating conditions to dampen the instabilities via high-speed injection of supplemental fuel. Timing of the control perturbations is determined by monitoring the combustor pressure for characteristic mediating trajectories which lead to misfire. The nonlinear nature of the system allows combustion stabilization to be achieved with relatively small injections of supplemental fuel. The control scheme is shown to be effective in reducing unburned-hydrocarbon emission levels and extending the practical operating limit of the pulsed combustor towards the lower flammability limit.

Motivation

The earliest known account of pulsed combustion is generally credited to Higgins for his 1777 description of experiments in which a hydrogen flame placed inside a vertical tube was often observed to produce a discernible hum. This so-called "singing flame" was later explored by scientists such as Faraday, Rijke and Rayleigh (Zinn, 1986). Efforts to develop practical applications for pulsed combustion did not occur until the twentieth century, with the first success being the V-1 "buzz bomb" rockets used by Germany in World War II (Foa, 1960). The next major application did not come until late in the twentieth century when residential heat pumps were developed which utilized pulsed combustion to increase fuel efficiency (Putnam *et al.*, 1986; Zinn, 1986). It has been shown that in various engineering systems, the use of a pulsed combustor instead of a more conventional steady-flow combustor has many advantages including thermal efficiencies on the order of 95%, higher heat- and mass-transfer rates and low emission levels of NO_x and CO (Arpaci *et al.*, 1993; Dec *et al.*, 1992; Gemmen *et al.*, 1993; Keller and Hongo, 1990; Putnam *et al.*, 1986).

As with other types of combustion, it is often desirable to operate pulsed combustors in the lean regime to minimize pollutant emission levels. Unfortunately, nonlinear combustion instabilities begin to develop as the equivalence ratio approaches the lower flammability limit. The instabilities lead to less efficient combustion and often misfire and flameout (Edwards *et al.*, 1997; Edwards *et al.*, 1998).

Analytical studies suggest that a primary factor in the development of combustion instabilities in the lean regime is the presence of small amounts of residual fuel and air left behind from one combustion cycle to the next. These small amounts of air and fuel combine with the incoming fresh charge to alter the equivalence ratio in the combustion chamber at the moment of ignition. The extreme sensitivity of ignition and flame propagation to these small changes in equivalence ratio creates an amplified sequence of enhanced and poor burns that subsequently feed into the next cycle. Similar behavior has been observed in spark-ignition engines (Daw *et al.*, 1996; Daw *et al.*, 1998; Wagner *et al.*, 1998; Scholl and Russ, 1999).

A previous model study of the combustor used in this investigation predicts that the combustion instabilities should appear in the form of a classic period-doubling bifurcation sequence as the equivalence ratio is reduced (Daw *et al.*, 1992; Daw *et al.*, 1995). However, experimental observations suggest that the route to instability follows a transition to quasi-periodicity and/or intermittency. As the equivalence ratio approaches the lower flammability limit, combustion instabilities are observed to develop that take the form of complex low-frequency ($\sim$10 Hz) fluctuations in the combustor pressure, superimposed on the normal pulsed-combustion events which occur at the acoustic frequency of the combustor ($\sim$100 Hz) (Edwards *et al.*, 1998).

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The development of a control scheme to reduce the occurrence of misfire and further extend the practical operating range of the pulsed combustor towards the lower flammability limit would provide further improvements in fuel efficiency and reductions in pollutant emission levels. In a study of the aforementioned analytical model, certain mediating trajectories were found to immediately proceed misfire. By imposing a small perturbation on the operating condition whenever the mediating trajectories are detected, the combustor model can be entrained into a more stable operating mode, avoiding misfire and delaying flameout (In *et al.*, 1997). The goal of this study is to demonstrate that such a control strategy is indeed capable of enhancing the performance of the pulsed combustor.

Experimental apparatus

The design of the pulsed combustor used in this study (shown schematically in **Figure 1**) is derived from the thermal pulse combustor developed at the former Morgantown Energy Technology Center (Richards *et al.*, 1991; Richards *et al.*, 1993) and consists of a main combustor body and an acoustically coupled tailpipe. The main body consists of a 52-cc mixing chamber and 295-cc combustion chamber which are separated by a honeycomb ceramic flameholder. The tailpipe is 0.9 m in length, giving the system a natural acoustic frequency of approximately 100 Hz.

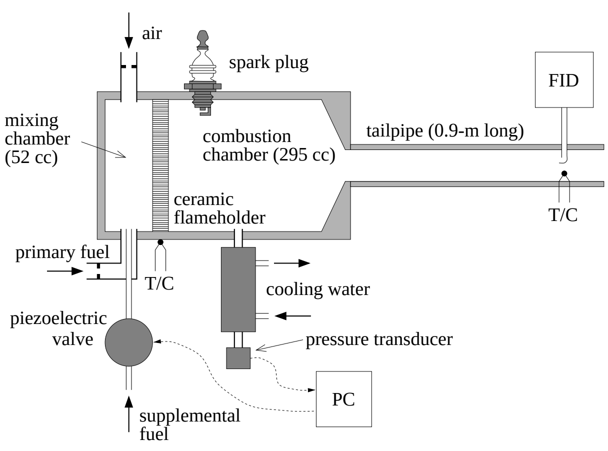


Figure 1: Schematic of the pulsed combustor.

Air and primary fuel (propane) are introduced at constant mass flow rates from separate supply lines each equipped with a critical-flow orifice. Swirl-inducing vanes are installed at the inlets to promote mixing; however, the streams do not completely mix, and the fresh charge introduced to the combustion chamber is stratified, especially at low flow rates. Initially, ignition is achieved using a spark plug installed immediately downstream of the ceramic flameholder; however, once initiated, combustion is self-sustaining. A piezoelectric pressure transducer (Kistler, model 206) is used for high-speed monitoring of the pressure oscillations inside the combustion chamber. Exhaust gas is sampled and analyzed using a flame ionization detector (FID) to measure unburned-hydrocarbon (UHC) emission levels. Thermocouples are used to monitor the exhaust-gas temperature, T_{exh}, and the combustor-wall temperature, T_w.

Injection of a small pulse of supplemental fuel was chosen as the control perturbation to make use of the nonlinear relationship between equivalence ratio and reaction rate. Optimal effect is achieved by injecting the supplemental fuel coaxially with the primary-fuel stream. The injection of the control perturbations is controlled by a low-flow piezoelectric valve (Maxtex, model MV-112) capable of cycling at 250 Hz.

The operating condition of the combustor is defined by the equivalence ratio, ϕ, and residence time, τ, (herein defined as the ratio of combustion-chamber volume to the volumetric flow rate of the mixture). By controlling the air and primary-fuel supply pressures and selecting the diameters of the critical-flow orifices, the residence time and the nominal equivalence ratio (without control perturbations) are set with an uncertainty level of $\pm 2\%$. The control perturbations momentarily increase the equivalence ratio significantly, but, on a time-averaged basis, the equivalence ratio is only slightly increased. Herein, the effective equivalence ratio, $\underline{\phi}$, is defined as being that which would exist if the control perturbations were introduced at a steady rate via the primary-fuel supply.

Results

The onset of the combustion instabilities was investigated by holding the residence time constant and decreasing the equivalence ratio from slightly rich conditions to the point at which the combustor experienced an unrecoverable flameout. **Figure 2** illustrates typical time-series segments of the combustor pressure, measured relative to the time-averaged mean pressure, recorded over a range of equivalence ratios at a residence time of 50 ms. At near-stoichiometric conditions, **Figure 2(a)**, the combustor pressure oscillates at the acoustic frequency of the system ($\sim$100 Hz); however, there are significant cycle-to-cycle fluctuations in magnitude. As the mixture is made increasingly fuel-lean, **Figure 2(b)**, the amplitude of the oscillations increase slightly and the cycle-to-cycle fluctuations in magnitude decrease significantly until the pressure oscillations become fairly regular with relatively minor fluctuations in magnitude, **Figure 2(c)**.

With further reductions in equivalence ratio, **Figure 2(d)**, cycle-to-cycle fluctuations increase sharply as

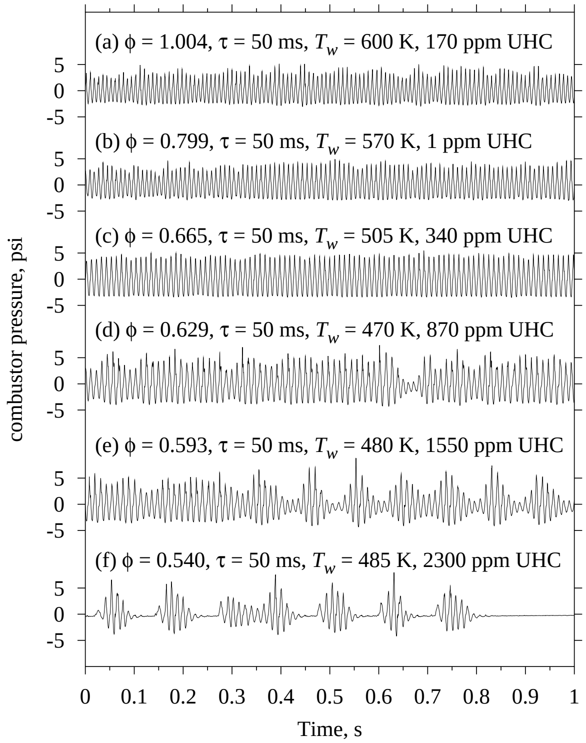


Figure 2: Time-series segments of the combustor pressure showing the effect of equivalence ratio on the performance of the pulsed combustor without control.

evidenced by modulations in combustor pressure and occasional misfires (*e.g.*, at t = 0.65 s). As the equivalence ratio approaches the lower flammability limit, **Figures 2(e)–2(f)**, the low-frequency fluctuation appears intermittently, and the period of the fluctuation increases. Misfires become more frequent and severe, occurring in long sequences allowing the combustor walls and ceramic flameholder to cool. Eventually, the cooling is sufficient to extinguish the self-sustaining reaction, at which point the pulsed combustor experiences an unrecoverable flameout, (**Figure 2(f)** at t = 0.8 s).

The control algorithm (outlined in **Figure 3**) is a simple feedback scheme that varies fuel injection depending upon combustion quality. The peak pressure of each pulse cycle is monitored to determine the average peak-to-trough cycle magnitude over the recent past. A control action (supplemental fuel injection) is initiated whenever the peak pressure of the current cycle is observed to fall below a pre-specified trigger level (specified as some percentage of the average cycle magnitude). After a pre-specified delay interval, the piezoelectric valve is opened for a pre-specified pulse duration. Successful control depends on proper selection of the trigger level, delay interval, pulse duration and the mass of supplemental fuel injected with each pulse. In this study, the values for these parameters were selected by the operator through trial-and-error; however, more sophisticated nonlinear optimization or neural-network schemes could easily be used.

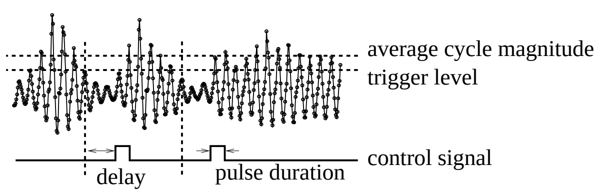
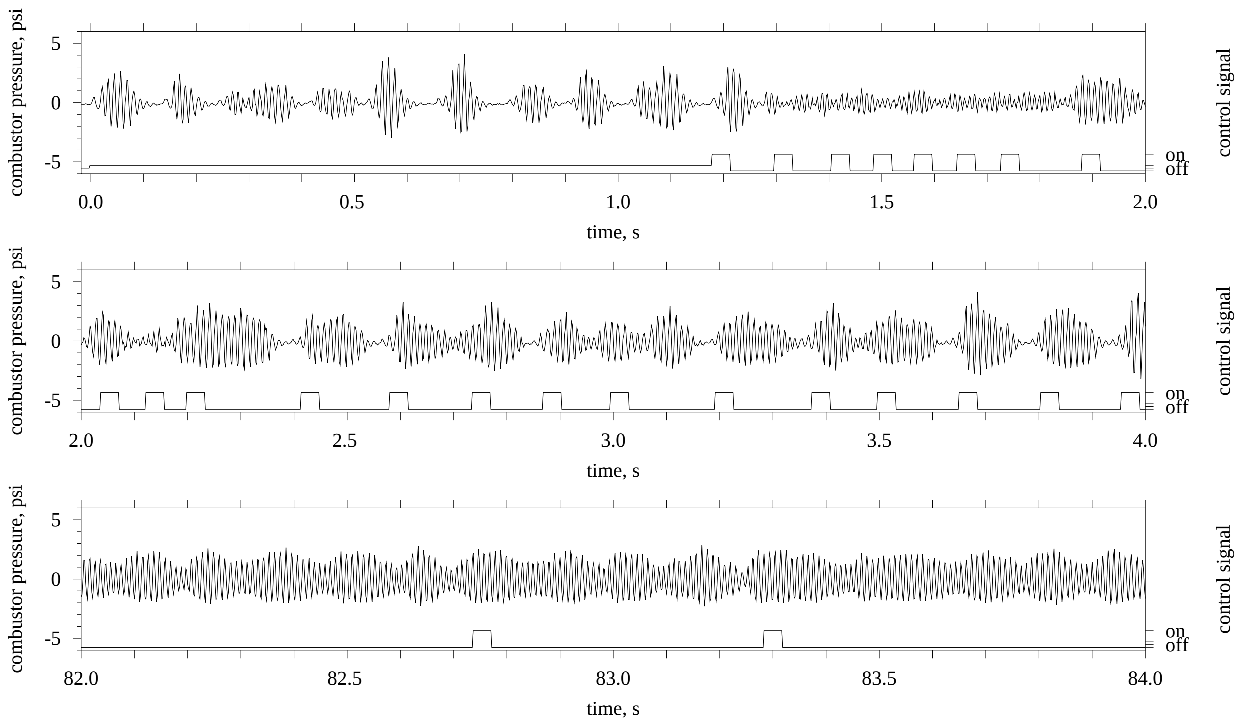


Figure 3: Schematic of control strategy.

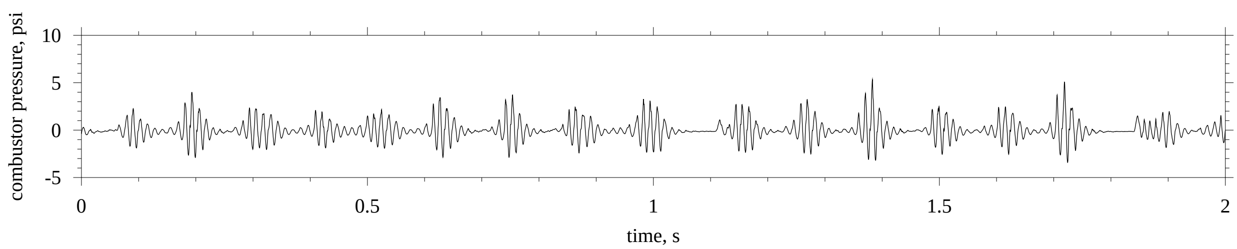
This scheme has proven to be more than adequate at realizing the control objectives. **Figure 4(a)** shows time-series segments of the combustor pressure collected while the pulsed combustor operates at a residence time of 75 ms and a nominal equivalence ratio of ϕ = 0.427. At this operating condition, the pulsed combustor experiences frequent and severe misfire and will eventually flame out unless control is applied.

Control is initiated at time t = 0 using a trigger level of 50% of the average cycle magnitude, a delay of 42 ms and a pulse duration of 33 ms. The first control action is applied after a brief learning period of approximately 1.2 s, momentarily driving the system into an erratic, low-amplitude behavior. Initially, control actions are frequent resulting in an effective equivalence ratio of $\bar{\phi} \approx 0.61$. Within 4 s, combustor performance is already improving, as evidenced by the slightly longer periods of stable operation without misfire. As the combustor becomes entrained in a more stable operating mode, the wall temperature increases, thereby further stabilizing the behavior. Control actions are required less frequently and within 90 s are only occasionally necessary to keep the system entrained in the stable operating mode indefinitely. At this point, the injections of supplemental fuel result in an effective equivalence ratio of $\bar{\phi} \approx 0.45$. It is important to note that the behavior of the combustor is much more efficient with control than if the mass flow rate of primary fuel were increased to yield a similar nominal equivalence ratio (**Figure 4(b)**).

Figure 5 demonstrates the effectiveness of the control algorithm in reducing the severity of the fluctuations in combustor-pressure magnitude at various nominal equivalence ratios. At ϕ = 0.665 (**Figure 5(a)**), the fluctuations in magnitude are greatly reduced with control; however, the system is occasionally pushed into a low-amplitude oscillation, suggesting that further optimization of the control parameters is needed. After control is terminated, the system remains entrained in the stable



(a) $\bar{\phi}$ = 0.45 (ϕ = 0.427, τ = 75 ms, T_w = 520 K, ∼80 ppm UHC

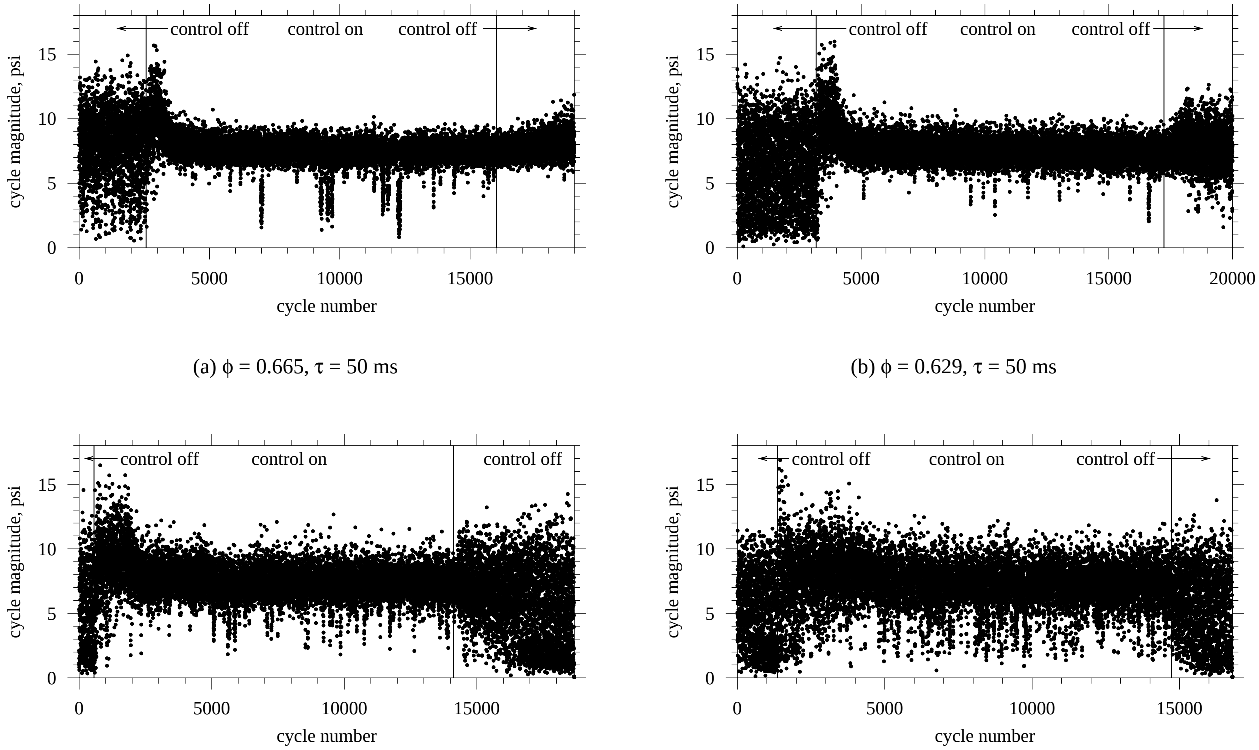


(b) ϕ = 0.45, τ = 75 ms, T_w = 450 K, ∼1600 ppm UHC

Figure 4: Time-series segments of combustor pressure showing the application of control and the effect of injecting an equivalent amount of fuel via the primary-fuel supply. Control parameters used in this example: trigger level = 50%; delay = 42 ms; pulse duration = 33 ms.

operating mode for some time before slowly diverging. Similar results are obtained at ϕ = 0.629 (**Figure 5(b)**). The reduction in magnitude fluctuation is slightly less, but the system is less frequently driven towards the low-amplitude oscillation. In both cases, the amount of supplemental fuel required once the system has stabilized only increases the effective equivalence ratio by ≈1–2%. At lower nominal equivalence ratios (**Figures 5(c)–5(d)**), control is less effective. Even though flameout is prevented, magnitude fluctuation is only slightly reduced, and misfires occur rather often. Furthermore, the amount of supplemental fuel injected increases the effective equivalence ratio by ≈5–7%. In these instances, the behavior with control is often less efficient than if the same amount of fuel were added via the primary-fuel supply.

A clearer sense of the effectiveness of the control strategy can be obtained through consideration of UHC emission levels. By limiting and in some cases eliminating misfire, the control strategy has proven to be very effective in reducing UHC emission levels, often by as much as a factor of ten, with only small changes in effective equivalence ratio (**Figure 6**). The fluctuations in the magnitude of the combustor pressure oscillations which



(a) ϕ = 0.665, τ = 50 ms

(b) ϕ = 0.629, τ = 50 ms

(c) ϕ = 0.593, τ = 50 ms

(d) ϕ = 0.558, τ = 50 ms

Figure 5: Combustor-pressure cycle-magnitude traces showing the effectiveness of control. Control parameters used in these examples: trigger level = 50%; delay = 42 ms; pulse duration = 33 ms.

occur at fuel-lean conditions have long been suspected of increasing the levels of NO_x production in pulsed combustors (Daw *et al.*, 1994; Daw *et al.*, 1995). Because the control algorithm is able to greatly reduce the severity of these fluctuations, NO_x emission levels are expected to be reduced as well, and additional studies to confirm this are underway.

Summary

A feedback control scheme has been developed to reduce the impact of combustion instabilities on the performance of a pulsed combustor operating in the lean regime. The control scheme is based on a strategy of injecting small amounts of supplemental fuel into the combustion chamber at critical moments of the pulse-modulation cycle. Timing of the control actions is based on continuous high-speed measurements of combustor pressure. Using this strategy it is possible to delay flame-out and reduce unburned-hydrocarbon emission levels as the lower flammability limit is approached.

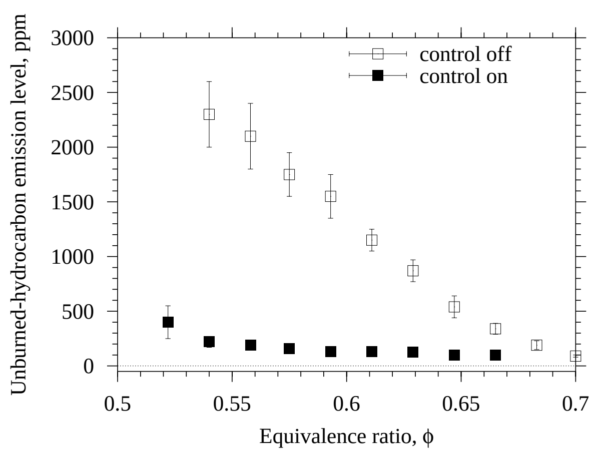


Figure 6: Unburned-hydrocarbon emission levels detected in the exhaust gases of the pulsed combustor over a range of equivalence ratios with and without control. τ = 50 ms.

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